TREE-RING EVIDENCE FOR CLIMATIC CHANGES IN WESTERN NORTH AMERICA

HAROLD C. FRITTS
Laboratory of Tree-Ring Research, The University of Arizona, Tucson, Ariz.

ABSTRACT

The relationships between climatic factors and fluctuations in dated tree-ring widths are statistically evaluated· A wide ring indicates that the year's climate was moist and cool, and a narrow ring dry and warm. In general, ring width relates to a 14-month period from June through July but most tree-ring chronologies exhibit a closer relationship with autumn, winter, and spring moisture than with summer moisture. The climatic relationships for evergreen trees are attributed largely to the influence of environmental factors on photosynthesis and the accumulation of food reserves. Under abnormally dry and warm conditions, especially during the autumn, winter, and spring, little food is accumulated, new cells are formed more slowly during the growing period, and the resulting ring is narrow.

Relative 10-yr. departures are calculated for the entire length of 26 tree-ring chronologies from western North America. Those portions after 1500 are used to map areas of high and low moisture. Periods of widespread drought are noted in 1576–1590, 1626–1635, 1776–1785, 1841–1850, 1871–1880, 1931–1940. Periods of widespread and above average moisture occurred during 1611–1625, 1641–1650, 1741–1755, 1826–1840, 1906–1920. The moist periods of 1611–1625, and 1906–1920 were most widespread and markedly above average.

1. INTRODUCTION

The details of the climatic history of the United States during recent centuries are not known. In this period, as in more ancient times, there is much indirect evidence of significant changes of climate. Dendroclimatic analysis represents an especially promising source of information on the chronology and character of such climatic changes, especially those in the semiarid regions of western North America.

It is the purpose of this report first to present some recent statistical analyses of the climatic factors influencing ring growth. This is followed by a brief discussion of the current theory concerning the model of tree growth and climate. In the last part, relative 10-yr. departures for ring growth are calculated from 26 North American tree-ring chronologies, and maps of these departures are constructed for the interval from A.D. 1501 to 1940.

2. ANALYSES OF TREE-RING AND CLIMATIC RELATIONSHIPS

Three study areas were chosen to center around three weather stations within forest stands where relatively homogeneous and long weather records are available. Fort Valley, Ariz., 35°16′ N., 111°44′ W., has an elevation of 7,345 ft. It is located near the San Francisco Peaks in a ponderosa pine (*Pinus ponderosa* Laws.) forest north of Flagstaff, Ariz. Pinyon pine (*Pinus edulis* Engelm.) occurs at slightly lower elevations and at greater distances from the main mountain mass. Idaho Springs, Colo., 39°45′ N., 105°33′ W., has an elevation of 7,556 ft. It is in a narrow valley with scattered stands of second growth ponderosa pine and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) occurring on the adjacent mountain slopes. Mesa Verde National Park, Colo., 37°12′ N., 108°30′ W., has an elevation of 6.960 ft. It is located on a southward sloping plateau which is forested with pinyon pine, occasional ponderosa pine, and Utah juniper (*Juniperus osteosperma* (Torr.) Little). Douglas-fir stands are restricted to deep canyon slopes and to the higher elevations.

Climatic summaries for the three stations are presented in table 1. Fort Valley records the highest annual precipitation. However, the annual precipitation of this region has been shown to decrease markedly with increasing distance from the San Francisco Mountain mass [1], and this is accompanied by vegetational changes to pinyon pine-juniper and then to grassland communities [7]. The seasonal precipitation regime exhibits two maxima associated with high frequencies of winter and summer storms. The Fort Valley and Idaho Springs stations exhibit comparable temperature regimes though the latter is 210 ft. higher. The annual precipitation at Idaho Springs is lower than at the other stations, but the monthly distribution exhibits one maximum centering around the tree growth season of May through August. The amount of annual precipitation at Mesa Verde National Park is intermediate between the other stations, but temperatures often average 7° F. higher, so that evapotranspiration probably reduces its effectiveness. Precipitation maxima occur during the winter and summer, but the relative amounts are more uniformly distributed throughout the entire year than at the other two stations.

TABLE 1.—*Climatic summary for the three weather stations used in screening analysis. (From U.S. Weather Bureau, Climatography of the United States, Climatic Summary of the United States—Supplement for 1931 Through 1952, No. 11-2, Arizona, and No. 11-5, Colorado)*

STATION	MONTHLY PRECIPITATION (Inches)												Annual total
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Fort Valley	2.35	2.43	2.02	1.66	.64	.59	2.50	3.76	1.81	1.51	1.11	2.46	22.84
Idaho Springs	.37	.56	.97	2.07	2.19	1.56	2.29	2.20	1.16	.85	.68	.37	15.27
Mesa Verde	1.86	2.14	1.97	1.22	1.02	.73	1.47	1.85	1.78	1.59	1.00	1.78	18.41
	MEAN MONTHLY TEMPERATURE (° F.)												Annual mean
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Fort Valley	24.5	27.2	32.7	40.7	47.6	55.5	62.9	61.5	55.4	44.9	34.1	27.9	42.9
Idaho Springs	25.2	27.5	32.3	40.9	48.1	57.1	62.7	61.6	55.0	45.3	34.2	28.6	43.2
Mesa Verde	29.4	33.1	38.7	48.4	57.2	67.1	73.3	71.1	64.0	52.6	39.6	32.0	50.5

During the summers of 1961 through 1963, several forest stands on semiarid sites were sampled near each weather station. Where possible, several samples were taken from a variety of sites and species so that differences in the tree-growth responses might be evaluated. Five or more dominant trees of comparable age were selected from each stand. Two or four radii were sampled from each tree using a Swedish increment corer. At first, a sample of four cores from five trees was used but later a sample of two cores from a larger number of trees was thought to be more representative of the regional tree-growth patterns. All rings on the increment cores were dated. Approximately the last 100 rings were analyzed but the length of record varied from 93 to 106 yr. because of the limited age of a few stands and differences in the year when the samples were taken. Ring widths on each core were measured, standardized, and analyzed by computer techniques [4].

The location, elevation, size, and several statistical characteristics of each sample are presented in table 2. These characteristics include: the first order serial correlation, average mean sensitivity [12], and standard deviation of the average chronology for the sampled group. The mean standard error of the group chronology and the percentages for three variance components are listed on the

TABLE 2.—*Sites, sample sizes, and statistical characteristics for chronologies used in screening analyses. Serial correlation, mean sensitivity, standard deviation, and standard error are calculated for the mean chronology of the sampled groups. The percent variance provides a measure of the relative variability in chronology of the whole group as compared to differences in chronologies among trees and among radii within trees*

SPECIES AND LOCATION	SITE	ELEVATION (ft.)	Years	Trees	Cores	Chronology Characteristics						
						Serial Corr.	Mean Sensitivity	Stand. Dev.	Stand. Error	% Variance		
										Radii	Trees	Group
DOUGLAS-FIR												
Fort Valley	NE-Facing Slope	8,500	102	5	20	0.66	0.29	0.40	0.079	22	7	71
Idaho Springs	N-Facing Slope	7,700	103	9	18	.23	.40	.37	.110	17	34	49
	NW-Facing Slope	8,000	103	9	18	.10	.47	.42	.086	14	19	67
Mesa Verde	Park Point	8,100	104	5	20	.58	.36	.44	.095	12	14	74
	Bobcat Canyon	6,900	104	5	20	.29	.61	.53	.086	11	8	81
	Old-Tree Canyon [1]	6,800	104	5	20	.30	.70	.68	.115	13	8	79
	Navajo Canyon [1]	6,500	106	5	20	.23	.66	.53	.091	10	9	81
PONDEROSA PINE												
Fort Valley	Mountain Slope	8,500	102	5	20	.65	.20	.27	.090	31	18	51
	Forest Interior	7,400	102	5	20	.54	.22	.28	.096	27	22	51
	Near Forest Border	7,300	103	5	20	.63	.49	.53	.103	11	9	80
	Forest Border	7,300	103	5	20	.70	.58	.68	.133	12	12	76
Idaho Springs	N-Facing Slope	7,700	103	7	14	.14	.44	.37	.117	21	28	51
	S-Facing Slope	7,900	103	17	34	.28	.47	.43	.076	21	17	62
Mesa Verde	Bobcat Canyon	7,000	93	5	20	.51	.23	.26	.090	29	24	47
	Moccasin Mesa	6,700	104	5	20	.03	.35	.31	.123	24	34	42
PINYON PINE												
Fort Valley	Upper Forest Border	7,300	103	5	20	.53	.31	.34	.093	20	16	64
	Lower Forest Border	6,300	103	5	20	.59	.44	.48	.102	15	13	72
Mesa Verde	Chapin Mesa Crest	8,400	104	5	20	.20	.32	.30	.092	22	24	54
	Chapin Mesa Mid	7,150	106	5	20	.32	.49	.45	.142	23	23	54
	Weth. Mesa Mid. [1]	7,000	104	5	20	.37	.49	.46	.107	13	17	70
	Chapin Mesa Low	6,700	104	5	20	.33	.59	.51	.101	17	11	72
	Bobcat Canyon	6,900	103	5	20	.52	.35	.42	.125	23	21	56
	Navajo C. E-Facing	6,600	106	5	20	.31	.56	.50	.119	20	14	66
	Navajo C. W-Facing	6,500	106	5	20	.60	.58	.59	.122	24	9	67
BRISTLECONE PINE												
Idaho Springs	Mount Evans	10,250	103	5	20	.37	.36	.33	.071	25	15	60

[1] Originally described and presented by Fritts, Smith, and Stokes [6].

right in table 2. The variance components measure the percentage of the variability due to differences in chronologies along the several radii, differences in chronologies among the several trees, as compared to the remaining variability in the chronology for the group. All computations are made with standardized tree-ring indices [4].

The consistently high variability and low error in tree-ring chronologies from the three areas demonstrate the high similarity in growth response for all trees within a group. Only the two samples of ponderosa pine from Mesa Verde exhibit more variability in chronologies between different radii and different trees than in the chronology of the group. Although catastrophic events such as fire, cutting, or insect infestation could affect the growth of the entire stand and thus alter the group chronology, the high variability from year to year and the consistency among widely scattered stands and different species that were sampled is evidence that climatic variation from year to year is responsible for a large part of the variation in widths of annual rings.

The three Douglas-fir samples from elevations under 7,000 ft. at Mesa Verde (table 2) exhibit high standard deviations and a high percent of variance in the group chronology. The same pattern appears in the lower elevation samples of ponderosa and pinyon pine, but these chronologies exhibit more site variability. Serial correlation is more pronounced in forest border ponderosa and pinyon pine than in forest border Douglas-fir.

Several of the samples described in table 2 were merged or augmented, and climatic relationships exhibited by each chronology were analyzed using the weather records from the neighboring station in a stepwise multiple regression analysis [3]. The monthly weather data were grouped into eight intervals prior to and concurrent with the season of growth. The total precipitation and average temperature were calculated for each interval. The intervals are: (1) previous June, (2) previous July, (3) previous August–September, (4) previous October–November, (5) previous December–February, (6) current March–May, (7) current June, and (8) current July. The climatic parameters of each interval were correlated with the corresponding ring-index values, and a multiple regression equation for predicting ring-indices was built in a stepwise fashion by entering variables in order of their correlation with the residual variance. The result is a multiple regression equation including only those variables which are found to be significantly related to the ring-width variability [3].

First, analyses were made on each chronology using only precipitation or only temperature during the eight intervals as possible predictors of growth. Where available, all three measures of temperature (maximum, mean, and minimum) were tried in separate analyses. Then in order to allow for serial correlation in the chronologies, the index values for the three preceding rings were included as possible variables, and all the above analyses were rerun. The inclusion of the three preceding indices generally improved prediction. The ranges of multiple correlations obtained in these analyses are:

1. 0.636–0.906 using precipitation and prior growth.
2. 0.000–0.839 using maximum temperature and prior growth.
3. 0.212–0.850 using mean temperature and prior growth.
4. 0.226–0.653 using minimum temperature and prior growth.

These results show that precipitation is generally more highly related to ring-width variation than is temperature.

Further analyses were made by including both precipitation and temperature during the eight intervals as independent variables. The products of temperature and precipitation were also included to allow for interaction. In a single analysis the total precipitation for each interval represents variables 1 through 8, the average maximum temperature for each interval represents variables 9 through 16, and the product of precipitation and average maximum temperature represents variables 17 through 24. Each analysis was run a second time with the ring indices for the three preceding years included as variables 25 through 27. Similar analyses were also run using mean temperature and average minimum temperature in place of average maximum temperature. As was observed in the earlier analyses, the inclusion of the three preceding growth indices generally improved prediction. The ranges of multiple correlations obtained in these analyses are:

1. 0.744–0.937 using precipitation, maximum temperatures, and prior growth.
2. 0.721–0.924 using precipitation, mean temperatures, and prior growth.
3. 0.741–0.947 using precipitation, minimum temperatures, and prior growth.

These results show a marked increase in prediction when both precipitation and temperature are used as predictors of growth. Temperature was entered as a variable and improved prediction over the use of precipitation alone in all analyses but two. These two exceptions are the forest interior ponderosa pine and pinyon pine samples near Fort Valley, Ariz., where only precipitation and previous growth were selected as the significant factors. In many cases the products of precipitation and temperature were entered so that the multiple regression equation was complex and difficult to evaluate by visual inspection. Therefore, to aid interpretation, selected values for precipitation and temperature were substituted into the final regression equations and the predicted ring width was calculated [6]. Using these computations it is possible to ascertain which climatic conditions for each interval relate to high and low growth. The variance ratios for the individual regression coefficients were used to test for significance and to arrange the climatic-interval effects in order of their importance. The regression coefficients for prior growth conditions were handled in a similar fashion.

TABLE 3.—*Stand locations, sample descriptions, and generalized results of screening analysis of tree-ring chronologies from 7 replicated samples of Douglas-fir. Climatic and growth conditions are those correlated with narrow annual rings and numbers in front of conditions indicate order of importance as determined from variance ratios. All variables exceed a 2.5 variance ratio*

Location	FORT VALLEY, ARIZONA	IDAHO SPRINGS, COLORADO		MESA VERDE, COLORADO			
Site	NE-Facing Slope	N-Facing Slope	NW-Facing Slope	Park Point	Bobcat Canyon	Old-Tree Can.[1]	Navajo Can.[1]
Elevation (ft.)	8,500	7,700	8,000	8,100	6,900	6,800	6,500
Miles from weather station	2	1	1	5	2	1	1
Years analyzed	49	57	57	41	40	41	38
Sample size	5 trees 20 cores	9 trees 18 cores	9 trees 18 cores	5 trees 20 cores	6 trees 24 cores	6 trees 30 cores	5 trees 20 cores
Variables used	precip. mean temp.	precip. mean temp.	precip. max. temp.	precip. min. temp.	precip. min. temp.	precip. max. temp.	precip. max. temp.
SEASON INTERVAL	CLIMATIC CONDITIONS ASSOCIATED WITH NARROW RINGS						
Prev. June		5 warm, dry	3 dry, warm	3 dry	6 dry, warm	7 dry or warm	7 dry or warm
Prev. July					5 cool		
Prev. Aug.-Sept		8 dry, warm	8 dry	5 dry	7 dry, warm	4 dry	4 dry
Prev. Oct.-Nov		6 dry, warm	9 dry	2 dry	4 dry, warm	2 dry	1 dry
Prev. Dec.-Feb	2 warm, dry	2 warm	7 dry, warm			6 dry	2 dry
Current Mar.-May	4 dry, cool	1 warm, dry	1 dry	4 warm, dry	3 dry	1 dry, cool	5 dry
Current June		4 dry, warm	4 dry, warm	1 dry	2 dry	5 dry, warm	6 dry
Current July	5 warm		6 warm, wet				
GROWTH INTERVAL	PRIOR GROWTH CONDITIONS ASSOCIATED WITH NARROW RINGS						
Prev. Year	1 low						
2 Years Prev		7 low	5 low				
3 Years Prev	3 low	3 low	2 low		1 low	3 low	3 low
Multiple Correlation	0.879	0.872	0.875	0.785	0.892	0.913	0.916
% Unexplained Variance	20.3	15.6	20.4	29.0	17.6	13.1	13.2

[1] Originally described and presented by Fritts, Smith, and Stokes [6].

TABLE 4.—*Stand locations, sample descriptions, and generalized results of screening analysis of tree-ring chronologies from 6 replicated samples of ponderosa pine. Climatic and growth conditions are those correlated with narrow annual rings and numbers in front of conditions indicate order of importance as determined from variance ratios. All variables exceed a 2.5 variance ratio*

Location	FORT VALLEY, ARIZONA		IDAHO SPRINGS, COLORADO		MESA VERDE, COLORADO	
Site	Forest Interior	Forest Border	N-Facing	S-Facing	Bobcat Canyon	Moccasin Mesa
Elevation (ft.)	7,950	7,300	7,700	7,900	7,000	6,700
Miles from Weather Station	1	17	1	1	2	5
Years Analyzed	49	49	57	57	40	41
Sample Size	10 trees 40 cores	10 trees 40 cores	7 trees 14 cores	17 trees 34 cores	5 trees 20 cores	5 trees 20 cores
Variables used	precip. mean temp.	precip. mean temp.	precip. max. temp.	precip. min. temp.	precip. min. temp.	precip. min. temp.
SEASON INTERVAL	CLIMATIC CONDITIONS ASSOCIATED WITH NARROW RINGS					
Prev. June	7 wet		3 dry, warm	5 warm		
Prev. July	4 wet		6 dry			7 dry, warm
Prev. Aug.-Sept				2 dry, cool	4 dry or warm	
Prev. Oct.-Nov	5 dry	6 warm	5 dry, warm	4 dry	6 warm, dry	
Prev. Dec.-Feb	3 dry	3 dry			1 dry, cool	1 warm
Current Mar.-May		2 dry	1 warm, dry	1 dry	5 warm	6 dry
Current June	8 dry		2 dry, warm	3 dry, warm		3 dry or warm
Current July	1 dry	5 dry			7 dry	5 dry
GROWTH INTERVAL	PRIOR GROWTH CONDITIONS ASSOCIATED WITH NARROW RINGS					
Previous Year	2 low	1 low			8 low	
2 Years Previous			4 low	6 low	3 low	4 low
3 Years Previous	6 low	4 low	7 low		2 low	2 low
Multiple Correlation	0.854	0.821	0.822	0.741	0.905	0.824
% Unexplained Variance	12.5	27.0	21.4	41.6	8.6	18.2

TABLE 5.—*Stand characteristics, sample descriptions, and generalized results of screening analysis of tree-ring chronologies from 7 replicated samples of pinyon pine at Mesa Verde National Park. Climatic and growth conditions are those correlated with narrow annual rings and numbers in front of conditions indicate order of importance as determined from variance ratios. All variables exceed a 2.5 variance ratio*

Location	CHAPIN MESA			WETHERILL MESA		NAVAJO CANYON	
Site	Crest	Middle	Low	Middle[1]	Bobcat Canyon	E-Facing	W-Facing
Elevation (ft.)	8,400	7,150	6,700	7,000	6,900	6,600	6,500
Miles from weather station	5	1	6	2	2	1	1
Years analyzed	41	38	41	41	40	38	38
Sample size	5 trees 20 cores	5 trees 20 cores	5 trees 20 cores	5 trees 20 cores	5 trees 20 cores	5 trees 20 cores	5 trees 20 cores
Variables used	precip. max. temp.	precip. max. temp.	precip. max. temp.	precip. max. temp.	precip. min. temp.	precip. min. temp.	precip. min. temp.
SEASON INTERVAL	CLIMATIC CONDITIONS ASSOCIATED WITH NARROW RINGS						
Prev. June					8 dry		3 dry
Prev. July							
Prev. Aug.-Sept	4 warm				2 warm, dry	4 warm, wet	6 warm
Prev. Oct.-Nov	1 dry	2 dry	2 dry	1 dry	4 dry	1 dry, warm	1 dry
Prev. Dec.-Feb	2 dry, cool	1 dry	1 dry	2 dry	1 dry	2 dry	2 dry, cool
Current Mar.-May	3 warm	4 warm, dry	3 dry, cool	5 dry, cool	6 dry	5 dry	7 dry, warm
Current June		3 warm			3 dry	3 dry	4 dry, cool
Current July	6 warm	5 warm	4 warm	4 warm		7 dry	5 dry, warm
GROWTH INTERVAL	PRIOR GROWTH CONDITIONS ASSOCIATED WITH NARROW RINGS						
Previous Year			5 low				
2 Years Previous	5 low			6 low	7 low		8 low
3 Years Previous			6 low	3 low	5 low	6 low	
Multiple Correlation	0.937	0.901	0.891	0.897	0.883	0.910	0.947
% Unexplained Variance	1.1	2.1	16.5	11.8	5.2	8.9	1.3

[1] Originally described and presented by Fritts, Smith, and Stokes [6].

The best predicting relationships for each analyzed chronology are presented in tables 3–6 by expressing the relationship as climate and prior growth conditions associated with the formation of narrow rings. Only those factors which proved significant are entered in the tables. Numbers indicate order of importance for the interval and the most significant climatic factor within the interval is entered first. Additional information provided in the tables is stand locations, sample descriptions, climatic variables used to obtain the equation, multiple correlation, and percent of unexplained variance. The last term is calculated by subtracting from the chronology variance its error variance and the variance explained by regression, and then dividing by the chronology variance to obtain a percent. The resulting value provides a measure of the relative failure of the analysis to obtain a perfect growth-climatic relationship.

Analyses for seven chronologies of Douglas-fir are shown in table 3. The samples are arranged from left to right in approximate order of increased aridity of site. The percentage of unexplained variance shows that the closest relationship between ring widths in Douglas-fir and climate occurs in the most arid sites. Moisture conditions from August through May appear to most closely relate to ring-width variation. The width of the third previous ring is highly significant, while the two previous ring widths appear unrelated.

With higher elevation and less aridity of site, the moisture during the current and previous June and July assumes more importance and the growth during the

TABLE 6.—*Stand locations, sample descriptions, and generalized results of screening analysis of tree-ring chronologies from replicated samples of pinyon pine north of Fort Valley, Ariz., and bristlecone pine on Mt. Evans, Colo., near Idaho Springs. Climatic and growth conditions are those correlated with narrow annual rings and numbers in front of conditions indicate order of importance as determined from variance ratios. All variables exceed a 2.5 variance ratio*

Location	Fort Valley, Arizona	Idaho Springs, Colorado
Species	Pinyon pine	Bristlecone pine
Elevation (ft.)	6,800	10,250
Miles from Weather Station	21	6
Years analyzed	49	57
Sample size	10 trees 40 cores	10 trees 20 cores
Variables used	precip. mean temp.	precip. max. temp.
	CLIMATIC CONDITIONS ASSOCIATED WITH NARROW RINGS	
Season interval		
Previous June		2 warm
Previous July		
Prev. Aug.-Sept		1 dry, warm
Prev. Oct.-Nov		6 dry
Prev. Dec.-Feb	1 dry	9 dry
Current Mar.-May	3 dry	3 dry
Current June		7 dry, warm
Current July		4 wet, warm
	PRIOR GROWTH CONDITIONS ASSOCIATED WITH NARROW RINGS	
Growth interval		
Previous Year	2 low	5 low
2 Years Previous		8 low
3 Years Previous	4 low	
Multiple correlation	0.788	0.778
Percent unexplained variance	20.7	36.4

two previous years may be more significant. The high significance of the width of the third previous ring in all but the Park Point sample indicates that climatic conditions which are favorable or unfavorable for ring growth may also influence other processes in the tree which become manifest three years later in the formation of a wide or narrow ring.

A generalized growth-climatic model for Douglas-fir may be obtained by averaging the results of the seven analyses in table 3. Conditions of low moisture and high temperature during March through May relate most significantly to narrow rings. Moisture and temperature during the current June, previous October through November, and previous December through February, are next in importance. Moisture and temperature conditions during the previous June and August through September appear to follow in importance, while climatic factors during the previous and current July exhibit no clear relationship to the annual ring increment.

Analyses for six samples of ponderosa pine are presented in table 4. The multiple correlation and percent unexplained variance exhibit no clear relationship with site. The Moccasin Mesa and forest border samples were collected 5 and 17 mi. from the weather stations, so it might be expected that these series would not exhibit a high relationship with the weather records especially during the summer months. It was noted that the south-facing slope chronology from Idaho Springs contained some nonclimatic variability probably related to site disturbance. This is a possible explanation for the low correlation and high unexplained variance obtained for that sample.

The variability in the intervals which relate to growth is sufficiently high to obscure any single pattern that can be discerned in the growth relationships for the different sites. An average picture for all six analyses indicates that low moisture and high temperature during December through May is most significantly related to narrow rings in ponderosa pine. Moisture and temperature during the previous October through November, and current June through July are next in importance while the climate during the previous June through September appears least important. A high relationship between growth and the widths of the three preceding rings is evident in the samples of ponderosa pine.

Analyses for seven pinyon pine samples at Mesa Verde National Park are presented in table 5, and a sample from near Fort Valley is presented in table 6. Ring widths in all pinyon pine samples at Mesa Verde are generally directly related to precipitation and inversely related to temperature. The relationship of growth to the three previous ring widths is less significant than for Douglas-fir and ponderosa pine. Considerable consistency is exhibited among the screening results for all eight samples. The climate for the interval December through February is either first or second in importance in all analyses. The previous October through November climate is almost as consistently significant, followed by the climate of March through May. Temperature and precipitation relationships during the current June and July also appear significant for the Mesa Verde samples.

The pinyon pine analyses differ from those of the other species in that the autumn, winter, and spring climate from October through May consistently account for a very large portion of the ring-chronology variance. The climate of the current June and July exerts a smaller influence. The absence of a relationship with the climate during October–November and June and July at Fort Valley is conceivably a result of the distance between the weather station and the sampled sites. This would introduce error especially in the correlation with summer and early autumn climate.

The results of an analysis of a single sample of bristlecone pine (*Pinus aristata* Engelm.) growing at its extreme lower limits on Mount Evans, Colo., are presented in table 6. A low multiple correlation and high percent unexplained variance in this analysis may be attributed both to possible site disturbance and to the distance and difference in elevation between the sample and the Idaho Springs weather station. However, the analysis suggests that the tree-ring chronology of this high elevation species relates most closely to the climate of the previous June, previous August through September, current March through May, and current July. The winter climate is significant but assumes a low order of importance. Since growth of this species appears to relate primarily to the highly variable summer climate, it is not surprising that correlations with the records of the relatively distant Idaho Springs weather station are low.

The above analyses show that variations in tree-ring widths from four southwestern conifer species clearly relate to variations in climatic parameters. There is a consistent, direct relationship of ring width with precipitation and an inverse relationship with temperature. The latter is less important, and in many cases, temperature appears to influence growth only if moisture is present in the soil. Opposite relationships occasionally appear in regression analyses, but coefficients exhibiting these opposite relationships are infrequent and not highly significant. Narrow rings in Douglas-fir and ponderosa pine imply low precipitation and high temperatures throughout the entire year, with a somewhat greater weight placed on the climate of autumn, winter, and spring. A narrow ring in pinyon pine implies a dry, warm previous autumn, winter, and spring and a hot June or July. A narrow ring in bristlecone pine implies a dry, warm climate during the year with greatest weight placed on the spring, summer, and autumn periods.

3. A SUGGESTED MODEL FOR THE PHYSIOLOGICAL RELATIONSHIPS CAUSING RING-WIDTH GROWTH TO CORRELATE WITH VARIATIONS IN CLIMATE

There are several recent studies which support and complement the above results. In two studies [7, 8] changes in tree-ring characteristics along a gradient

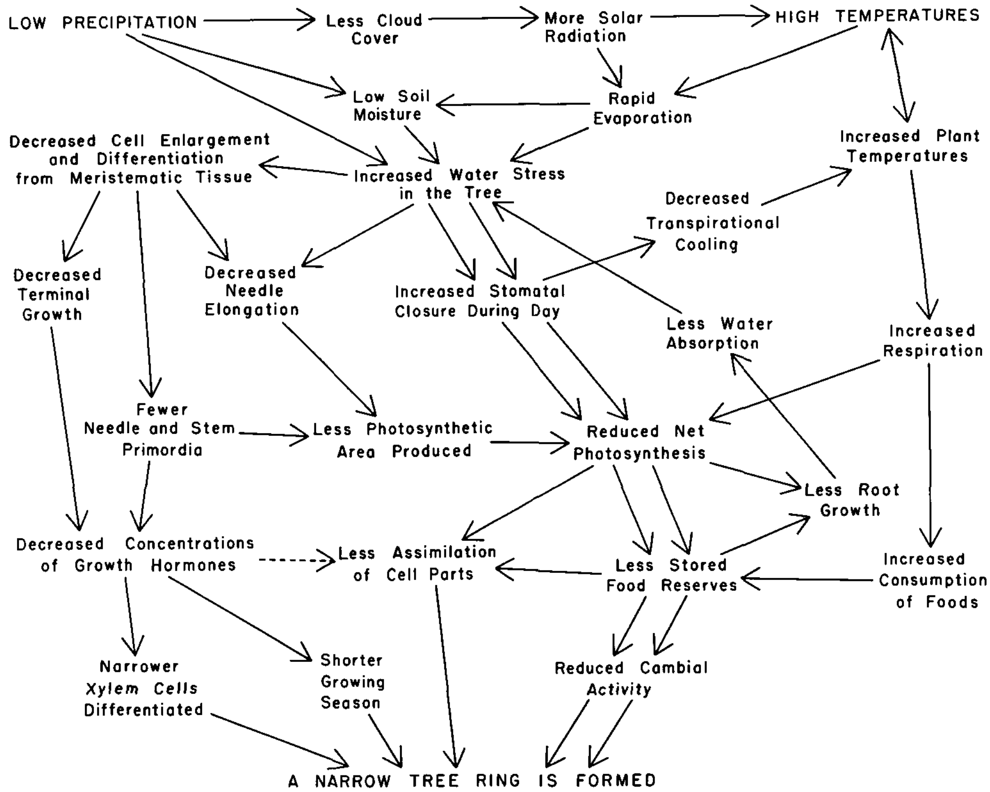

FIGURE 1.—A schematic diagram of the model hypothesized for the relationships between low precipitation and high temperatures and the production of a narrow tree ring.

from the forest interior to the forest border are analyzed. A decrease in the forest density, which indicates increased site aridity, is associated with greater year-to-year variability in the tree-ring chronologies, higher correlations among trees, and higher variances in common among trees within sites. The authors suggest that on semiarid sites, climate is most frequently limiting to plant processes, and therefore the variations in ring widths exhibit the highest relationship to variations in climate. Schulman [12] had previously recognized this phenomenon and applied it to dendroclimatic investigations by selecting and studying only trees from semiarid sites.

A study by Fritts, Smith, and Stokes [6] represents a detailed analysis of the biological and statistical relationships dealt with in this report. Among other things they analyze radial growth and needle length in pinyon pine and Douglas-fir, and relate them to site factors and the climatic regime. They analyze statistical samples from Mesa Verde (three of which appear in this report) and describe the procedures and results of screening analyses. They apply their findings to the reconstruction of a drought sequence at Mesa Verde during prehistoric times, using a Douglas-fir chronology which extends from A.D. 435 to A.D. 1963.

These authors propose that the formation of a wide or narrow tree ring is largely a function of the available food supplies which are initially manufactured by photosynthesis and accumulated throughout the previous year. Climate influences ring growth primarily through its control of photosynthesis and other processes affecting the accumulation of stored foods. They suggest that cambial activity and growth in the spring and early summer usually continue until the stored food is expended. However, they recognize that climatic conditions can sometimes directly induce the cessation of growth. The proposed model is schematically diagramed in figure 1.

Precipitation is the primary climatic control but temperature may modify its influence. Both factors affect the water relations of the tree, which in turn, govern photosynthesis and the accumulation of food. Temperature may also directly influence food accumulation through its control of photosynthesis, respiration, and the assimilation of foods in the plant. Fritts [5] presents direct evidence that during hot and dry periods food consumption frequently exceeds food production in conifers on lower forest border sites, but during cooler and more moist periods, photosynthesis rates are higher and respiration rates lower, water relations less critical and the net accumulation of photosynthate may be greater. High rates of net photosynthesis have been measured during winter days, even though the trees may be frozen at night [5].

The left portion of the diagram in figure 1 shows how water relations during the time of growth may also influence ring width. Water stress may reduce cell enlargement in the meristems of the growing buds. This may reduce the concentration of hormones that are produced by the meristems, and these low hormone concentrations may reduce cambial activity or cell enlargement and cause the ring to be narrow. High water stress may also decrease the number and size of new stems and leaves, and thus affect the amount of new photosynthetic area that is produced. With less photosynthetic area, the efficiency with which the tree responds to climate is reduced, so that less food can be made, and the rings during subsequent years will be proportionately narrower. This relationship could produce the serial correlation which is evident in the above statistical analyses.

It may be concluded from the results of the individual screening analyses that there is a close relationship between the widths of annual rings from trees on semiarid sites and variations in the aridity of the yearly climates. Growth analyses and preliminary results from physiological studies indicate that these relationships may be largely attributed to the accumulation of stored foods in the tree during periods when neither moisture nor temperature are limiting to the food-accumulating processes. Therefore, the ring width represents an integration of the favorableness of the environment of approximately a year's duration, though direct effects of environment on growth and relationships producing serial correlation are complicating factors. In general it may be inferred that the wider the ring, the more moist and cool was the climate.

Chronologies from different species and sites may measure somewhat different seasonal periods. For example, the ring widths of extremely low elevation trees, such as lower forest border pinyon pine, may be controlled largely by moisture during the autumn, winter, and spring because high summer temperatures rapidly evaporate soil moisture and are unfavorable for accumulation of foods. Likewise, ring widths of high elevation arid-site trees, such as bristlecone pine, may be more influenced by precipitation during spring, summer, and autumn because extremely low temperatures during the winter period prevent photosynthesis and food accumulation from occurring at that time. Since most dendroclimatic work has dealt with sites at intermediate elevations, it may be inferred that most chronologies provide relatively reliable estimates of the occurrence of drought for the entire year beginning in June and ending in the following June or July. Schulman [12] came to the same general conclusion, though he did not consider temperature as a factor and his analyses accounted for less variance.

4. DENDROCLIMATIC ANALYSIS OF WESTERN NORTH AMERICA

Tree-ring chronologies from 26 stations through western North America were selected for their location, length, and reliability (table 7). Douglas-fir chronologies were generally selected, but in some areas, the best chronologies available were for other species. All chronologies were converted to standardized ring-width indices, so they are relatively free of changes arising from growth and maturation of individual trees.

Whenever possible, chronologies based upon only a few trees were avoided for they exhibit the most error. However, chronologies 1, 3, 10, 15, and 24 (table 7), which are based upon the fewest number of trees, are strategically located and are used only for lack of better data. Recent analyses indicate that the error in a small sample, such as five trees, may not be excessive if care is taken to select comparable sites, but any further reduction in sample size greatly inflates the error component. Because the earliest portions of most chronologies, especially the small samples, may be derived from a very limited number of trees, these early chronologies undoubtedly contain the most error. This error is further inflated by the use of archaeological materials to extend chronologies into still earlier times.

All 26 chronologies include the years 1651 through 1920

TABLE 7.—*Tree-ring chronologies presented in table 8 and plotted on maps in figures 2–10. BCP=bristlecone pine, BCS=big cone spruce* (Pseudotsuga macrocarpa *(Vasey) Mayr), DF=Douglas-fir, JP=Jeffrey pine* (Pinus jeffreyi *Grev. and Balf.), LP=limber pine* (P. flexilis *James), Pnn=pinyon pine, PP=ponderosa pine*

No.	NAME	LATITUDE NORTH		LONGITUDE WEST		SPECIES	MAX. NO. of TREES	PERIOD USED	SOURCE (Ref. No.)
		°	′	°	′				
1	Durango, Mexico	23	48	105	36	DF	5	1641–1940	[12], Table 81
2	Big Bend, Tex	29	13	103	19	DF	15	1646–1945	[12], Table 73
3	Casas Grandes, Mexico	30	07	108	22	DF, PP, Pnn	6	1526–1960	[13]
4	Southern Arizona	32	14	110	17	DF	27	1416–1950	[12], Table 66
5	Cloudcroft, N. Mex	32	56	105	45	DF	8	1516–1960	[15]
6	S. Calif., Big Cone Spruce	33	59	117	25	BCS	60	1386–1950	[12], Table 78
7	Upper Rio Grande, N. Mex	35	43	106	06	DF, PP, Pnn	11	911–1930	[14]
8	San Bernardino Mts., Calif	34	10	117	00	PP	12	1351–1930	[12], Table 79
9	Flagstaff, Ariz	35	12	111	40	PP	23	576–1960	[2]
10	Navajo Natl. Monument, Ariz	36	41	110	32	DF	5	701–1955	[10]
11	Mesa Verde Natl. Park, Colo	37	12	108	28	DF	12	736–1945	[9]
12	White Mts., Calif	37	24	118	10	BCP	10	801–1950	Schulman (unpublished data).
13	Arkansas River, Colo	38	29	105	57	DF	16	1431–1950	[12], Table 45
14	South Platte River, Colo	39	21	105	35	DF	15	1426–1940	[12], Table 44
15	N.E. California	40	25	120	38	PP	5	1486–1930	[12], Table 76
16	S.E. Oregon	42	12	120	20	PP	15	1456–1930	[12], Table 75
17	Snake River, Idaho	44	03	112	51	DF	20	1286–1950	[12], Table 36
18	Upper Missouri DF, Mont	45	39	111	33	DF	52	1306–1950	[12], Table 40
19	Columbia River, Wash	48	58	119	29	DF, PP	29	1651–1940	[12], Table 33
20	Banff, Canada	51	09	115	29	DF	33	1461–1950	[12], Table 31
21	Fraser River, Canada	51	55	121	52	DF, PP	41	1421–1940	[12], Table 28
22	E. Central California	37	45	119	02	JP	14	1356–1940	[12], Table 77
23	Nine Mile Canyon, Utah	39	46	110	27	DF	18	1201–1945	[11]
24	North Platte River, Colo	40	55	106	19	DF	6	1336–1945	[12], Table 43
25	Upper Missouri LP, Mont	45	19	111	12	LP	21	981–1950	[12], Table 41
26	Jasper, Canada	52	54	118	04	DF	8	1541–1945	[12], Table 30

TABLE 8.—*Relative 10-yr. departures at 5-yr. intervals for 26 tree-ring chronologies from western North America. Stations are identified and described in table 7.*

INTERVAL	STATION NUMBER 7	9	10	11	23	12	17	25
551- 560								
556- 565								
561- 570								
566- 575								
571- 580								
576- 585		0.31						
581- 590		1.12						
586- 595		0.62						
591- 600		0.04						
596- 605		−0.01						
601- 610		0.09						
606- 615		−0.54						
611- 620		−0.58						
616- 625		0.87						
621- 630		0.83						
626- 635		−0.37						
631- 640		0.08						
636- 645		0.63						
641- 650		−0.58						
646- 655		−1.41						
651- 660		−0.78						
656- 665		−0.73						
661- 670		−0.61						
666- 675		0.55						
671- 680		0.57						
676- 685		0.37						
681- 690		0.61						
686- 695		0.48						
691- 700		−0.44						
696- 705		−1.11						
701- 710		−0.77	0.07					
706- 715		−0.70	−0.38					
711- 720		−0.43	−0.51					
716- 725		−0.38	0.11					
721- 730		0.02	0.82					
726- 735		0.80	0.72					
731- 740		0.24	−0.31					
736- 745		−0.69	−0.33	0.08				
741- 750		−0.62	0.02	0.23				
746- 755		−0.57	−0.11	0.18				
751- 760		−0.53	−0.56	−0.24				
756- 765		−0.41	−1.31	−0.40				
761- 770		−0.25	−1.49	−0.13				
766- 775		−0.08	−1.24	−0.48				
771- 780		−0.44	−1.09	−0.61				
776- 785		−0.46	−0.77	−0.49				
781- 790		−0.24	−0.67	0.10				
786- 795		−0.44	−0.53	0.45				
791- 800		−0.49	0.27	0.12				
796- 805		0.72	1.11	0.39				
801- 810		0.65	0.33	−0.02		−0.54		
806- 815		−0.06	−0.42	0.03		−0.61		
811- 820		−0.07	−0.49	0.27		−0.47		
816- 825		−0.41	−0.57	−0.11		−0.22		
821- 830		−0.11	−0.39	−0.38		0.01		
826- 835		0.56	−0.18	−0.64		0.38		
831- 840		0.11	−0.02	−0.47		0.16		
836- 845		−0.77	−0.36	−0.35		−0.27		
841- 850		−0.79	−0.35	−0.53		−0.20		
846- 855		−0.41	0.06	0.47		−0.03		
851- 860		0.43	0.54	1.28		0.57		
856- 865		0.45	0.85	0.79		0.47		
861- 870		−0.37	1.06	0.10		−0.44		
866- 875		−0.57	0.22	−0.27		−0.55		
871- 880		−0.38	−1.04	−0.40		−0.17		
876- 885		−0.82	−1.24	−0.67		−0.10		
881- 890		−0.52	−1.19	−0.12		0.06		
886- 895		−0.25	−0.96	−0.25		0.65		
891- 900		0.06	−0.34	0.59		1.02		
896- 905		−0.17	−0.13	0.83		0.30		
901- 910		−1.02	−0.56	−0.49		−0.32		
906- 915		−0.22	−0.58	0.32		−0.03		
911- 920	−0.40	0.21	−0.05	1.06		0.33		
916 925	−0.70	−0.82	−0.33	−0.02		−0.13		
921- 930	−0.48	−0.62	−0.51	−0.40		−0.17		

INTERVAL	STATION NUMBER 7	9	10	11	23	12	17	25
926- 935	0.30	−0.22	−0.10	0.09		0.16		
931- 940	0.62	−0.20	0.07	−0.11		0.40		
936- 945	0.54	1.03	0.14	0.14		0.45		
941- 950	0.27	1.61	0.30	0.91		0.36		
946- 955	−0.45	0.31	0.08	0.49		0.28		
951- 960	−0.14	−1.05	0.02	0.17		−0.12		
956- 965	0.61	−0.40	0.38	0.45		0.07		
961- 970	0.96	0.11	0.33	0.41		0.25		
966- 975	0.28	−0.12	0.48	0.61		0.07		
971- 980	−0.54	−0.42	0.21	0.16		0.08		
976- 985	−0.48	−0.90	−0.17	−0.71		−0.25		
981- 990	0.24	0.15	1.24	0.44		−0.14		−0.08
986- 995	0.76	0.34	0.91	0.72		0.17		−0.53
991-1000	0.34	−0.52	−0.47	−0.13		0.06		−1.52
996-1005	−0.24	−0.57	−0.51	−0.38		0.02		−0.50
1001-1010	−0.85	−0.21	−0.42	−0.42		0.17		0.28
1006-1015	−0.76	0.11	−0.01	0.09		0.05		−0.41
1011-1020	−0.50	−0.01	−0.17	0.16		0.26		−0.91
1016-1025	0.12	0.11	−0.13	0.70		0.62		−0.72
1021-1030	1.04	0.34	−0.01	0.70		0.15		−0.31
1026-1035	0.96	0.44	−0.22	−0.36		−0.07		0.22
1031-1040	0.30	−0.14	−0.60	−0.57		0.36		0.76
1036-1045	−0.31	−0.39	−0.99	−0.36		0.67		1.01
1041-1050	−0.53	−0.10	−0.77	−0.34		0.47		0.41
1046-1055	−0.08	−0.11	0.17	0.09		0.15		−0.71
1051-1060	−0.20	−0.04	0.65	0.59		−0.09		−0.70
1056-1065	0.36	0.11	1.22	1.64		0.60		0.18
1061-1070	0.23	−0.44	0.94	1.62		0.28		−0.00
1066-1075	−0.74	−0.78	−0.49	0.92		−0.55		−0.45
1071-1080	−0.48	0.09	−0.17	1.60		−0.12		−0.47
1076-1085	−0.42	0.66	0.53	0.94		0.35		−0.17
1081-1090	−0.72	0.11	0.21	−0.10		0.77		0.21
1086-1095	−0.69	−0.68	−0.50	−0.53		0.65		−0.52
1091-1100	−0.65	−0.81	−0.99	−0.99		0.53		−0.87
1096-1105	−0.18	−0.63	−0.49	−0.44		0.57		−0.38
1101-1110	0.04	−0.52	−0.27	−0.13		0.81		0.01
1106-1115	0.27	0.20	−0.31	0.23		1.22		0.37
1111-1120	1.26	0.67	0.69	1.22		0.95		0.90
1116-1125	1.19	0.47	1.35	1.17		0.50		−0.29
1121-1130	0.47	0.54	1.15	0.45		0.18		−1.47
1126-1135	−0.33	0.14	−0.34	−0.18		−0.38		−0.92
1131-1140	−0.87	−0.51	−1.48	−0.56		−0.22		1.48
1136-1145	−0.26	−0.36	−1.10	0.15		0.22		2.78
1141-1150	−0.48	−0.26	−1.27	−0.04		−0.57		1.53
1146-1155	−0.55	−0.16	−1.48	−0.42		−0.81		−0.20
1151-1160	−0.49	−0.23	−0.92	−0.29		−0.07		−1.32
1156-1165	−0.28	−0.12	−0.34	0.11		0.13		−1.17
1161-1170	0.17	−0.08	−0.43	0.18		0.07		−0.80
1166-1175	0.32	−0.26	−1.02	−0.12		0.12		−0.89
1171-1180	0.68	−0.08	−0.69	0.09		−0.13		−0.84
1176-1185	0.51	0.11	−0.11	−0.21		0.13		−0.41
1181-1190	−0.25	0.12	−0.74	−0.35		0.21		0.40
1186-1195	−0.04	−0.31	−1.13	−0.16		0.02		0.64
1191-1200	0.93	−0.10	−0.23	0.11		0.06		0.05
1196-1205	0.83	0.95	0.70	0.15		0.55		0.03
1201-1210	0.62	0.96	0.81	−0.05	−0.32	0.65		−0.30
1206-1215	−0.11	−0.09	0.75	0.16	0.16	0.63		0.23
1211-1220	−0.93	−1.03	−0.20	−0.25	0.24	0.61		0.71
1216-1225	−0.91	−1.26	−0.88	−0.49	−0.25	0.11		0.17
1221-1230	−0.31	−0.64	−0.61	−0.04	0.11	0.13		0.98
1226-1235	0.34	−0.45	−0.55	−0.02	0.13	0.21		1.14
1231-1240	0.81	−0.34	−0.28	0.26	−0.30	0.02		0.67
1236-1245	0.97	0.07	0.26	0.25	0.05	0.08		0.32
1241-1250	0.23	−0.06	0.40	−0.03	0.67	0.56		−0.18
1246-1255	−0.78	−0.68	−0.17	−0.23	0.14	−0.03		−0.30
1251-1260	−0.45	0.37	0.09	−0.28	0.30	−0.42		−1.07
1256-1265	−0.07	0.80	−0.01	−0.08	0.16	−0.06		−1.44
1261-1270	−0.10	−0.19	−0.83	0.10	−0.61	0.18		−0.58
1266-1275	−0.17	−0.03	−0.38	0.06	−0.67	0.16		−0.12
1271-1280	−0.76	−0.22	−0.81	−0.60	−0.75	−0.22		−0.68
1276-1285	−0.63	−0.67	−1.30	−0.79	−0.93	−0.54		−0.61
1281-1290	−0.10	−0.97	−1.26	−0.33	−1.03	−0.69		0.40
1286-1295	−0.29	−1.13	−1.43	−0.36	−0.92	−0.68	−0.06	0.92
1291-1300	−0.19	−1.04	−1.36	−0.55	−0.60	−0.86	0.23	0.67
1296-1305	0.79	−0.18	−0.35	−0.06	−0.05	−0.61	0.14	−0.39

Table 8.—Continued

INTERVAL	STATION NUMBER 1	2	3	4	5	6	7	8	9	10	11	13	14	23	24	12	22	15	16	17	25	18	19	20	26	21
1301-1310							0.90		0.77	0.28	0.08			0.04		-0.32				-0.19	-0.86					
1306-1315							0.35		1.07	0.22	0.39			0.16		0.20				0.14	-0.08	-0.06				
1311-1320							0.17		0.46	0.01	0.34			-0.01		0.68				-0.20	-0.16	0.07				
1316-1325							0.06		-0.48	-0.58	-0.04			-0.34		0.42				-0.71	-0.34	-0.42				
1321-1330							-0.09		0.12	-0.31	0.25			-0.21		0.66				0.14	0.65	0.36				
1326-1335							-0.13		1.01	0.12	0.68			0.54		1.33				0.81	1.64	1.58				
1331-1340							-0.36		0.55	0.39	0.75			0.78		1.20				-0.00	0.95	0.69				
1336-1345							-0.33		0.10	0.13	-0.03			0.27	-0.17	1.31				-0.51	0.20	0.11				
1341-1350							-0.06		-0.35	-0.41	-0.51			-0.07	-0.63	1.93				-0.10	0.38	0.32				
1346-1355							0.58		-0.84	-0.45	-0.36			-0.13	-0.49	1.46				-0.02	0.46	-0.09				
1351-1360							1.28	-0.69	-0.25	0.23	0.17			0.36	-0.29	1.45				-0.19	0.51	-0.26				
1356-1365							0.54	-0.63	-0.13	-0.24	-0.26			-0.27	0.37	0.72	0.21			-0.37	-0.39	-0.54				
1361-1370							0.03	-0.40	-0.24	-0.44	-0.36			-0.54	0.34	0.40	-0.26			0.13	-0.45	-0.39				
1366-1375							0.17	-0.07	-0.20	0.29	0.12			0.54	0.50	1.16	0.66			0.48	-0.00	0.01				
1371-1380							0.23	0.24	-0.62	0.17	0.10			0.59	0.95	0.42	0.07			-0.19	-0.36	-0.27				
1376-1385							0.29	0.53	-0.04	0.58	0.89			0.25	-0.06	0.33	-0.32			-0.61	-0.59	-0.49				
1381-1390							0.25	0.75	-0.04	0.49	0.86			0.20	0.16	0.53	0.51			-0.04	-0.30	-0.34				
1386-1395						0.58	0.33	0.39	-1.16	-0.68	0.07			0.27	0.63	0.76	0.30			0.41	0.11	-0.15				
1391-1400						0.90	0.10	-0.15	-0.98	-1.35	-0.48			0.20	-0.04	0.71	0.70			-0.25	-0.54	-0.53				
1396-1405						0.42	0.26	-0.08	-0.50	-1.13	-0.93			-0.45	-0.77	0.25	0.60			-0.32	-0.59	-0.90				
1401-1410						-0.24	0.50	-0.17	-0.81	-0.33	-0.06			-0.72	-1.13	0.31	-0.32			-0.05	0.35	-0.40				
1406-1415						-0.17	0.27	-0.10	-0.31	0.17	0.09			-0.31	0.35	0.22	-0.40			0.06	0.53	-0.10				
1411-1420						-0.30	-0.17	0.01	0.25	0.45	-0.55			0.32	0.97	0.73	-0.07			0.63	0.13	-0.05				
1416-1425				-0.17		-0.62	-0.90	-0.34	-0.43	0.13	-0.65			0.51	-0.21	1.42	-0.00			0.51	0.40	0.36				
1421-1430				1.16		-0.04	-0.19	-0.40	-0.59	0.42	0.00			0.56	0.18	0.96	-0.63			0.03	0.67	0.46				0.11
1426-1435				1.09		0.19	0.70	-0.41	0.01	1.06	0.60		-0.50	0.37	1.59	0.06	-1.42			-0.54	0.15	0.44				-0.07
1431-1440				-0.57		-0.24	0.14	-0.56	-0.02	0.02	0.12	-0.35	0.01	-0.01	1.37	-0.06	-1.28			-1.19	-0.99	-0.40				-0.25
1436-1445				-1.09		0.37	-0.12	-0.77	-0.56	-0.42	-0.07	-0.61	0.35	-0.28	0.64	-0.03	-1.33			-0.32	-0.55	-0.19				-0.22
1441-1450				-1.31		0.33	-0.06	-1.00	-0.44	-0.46	-0.40	-0.76	0.52	-0.50	-0.50	-0.48	-1.15			0.81	-0.61	0.28				0.11
1446-1455				-1.31		-0.26	-0.61	-0.70	0.13	-0.50	-0.48	-0.65	-0.13	0.02	-1.36	-0.29	-1.34			1.18	-0.36	-0.06				-0.10
1451-1460				0.19		-0.28	-0.59	-0.12	0.21	-0.19	-0.24	-0.42	-0.33	0.05	-0.70	-0.10	-1.95			1.16	0.70	-0.06				-0.38
1456-1465				1.04		-0.28	-0.37	-0.11	-0.00	-0.39	-0.65	0.25	0.05	-0.48	0.31	0.07	-0.64		0.68	0.73	0.61	0.07				0.12
1461-1470				0.82		-0.07	0.22	0.04	-0.10	-0.05	-0.29	0.60	-0.08	0.22	0.18	0.71	0.45		0.10	0.56	0.69	0.37		-0.05		-0.06
1466-1475				0.76		0.10	-0.38	0.63	-0.11	-0.47	-0.29	-0.03	-0.46	-0.24	-0.23	0.37	0.49		0.43	-0.09	0.14	-0.08		-0.06		-0.06
1471-1480				1.35		0.17	-1.13	0.86	0.36	-0.52	-0.45	-0.14	-0.17	-0.66	-0.16	0.16	-0.33		0.10	-0.84	0.28	-0.14		-0.20		0.08
1476-1485				1.51		0.76	-0.33	0.73	0.82	0.63	0.38	-0.05	0.47	0.41	0.58	0.53	-0.71		-0.55	-0.94	0.43	0.05		-0.45		0.36
1481-1490				1.15		0.82	0.38	0.34	0.40	0.87	0.78	0.20	0.55	0.85	1.42	1.28	-0.06		0.01	-0.41	0.34	0.37		-0.22		0.97
1486-1495				0.30		-0.12	0.06	0.15	0.05	0.65	0.82	0.32	0.10	0.54	1.16	1.21	0.04	-0.58	0.52	-0.23	0.16	0.04		-0.02		0.27
1491-1500				-0.46		-0.76	-0.40	-0.20	-0.09	0.01	0.34	-0.19	-0.40	-0.41	0.09	-0.43	-0.95	-1.23	-0.14	-0.45	-0.67	-0.71		-0.26		-0.24
1496-1505				0.38		-0.25	-0.03	-0.50	-0.27	-0.32	-0.15	-0.19	-0.64	-0.90	0.03	-0.60	-1.39	-1.10	-0.67	-0.48	-1.07	-0.67		-0.19		-0.07
1501-1510				1.61		-0.21	0.11	-0.59	-0.46	-0.23	-0.35	-0.47	-0.22	-0.71	0.84	0.23	-0.27	-0.55	-0.21	-0.49	-0.26	0.38		-0.32		-0.21
1506-1515				0.91		-0.41	0.39	-0.58	-0.52	0.54	0.26	-0.43	0.34	-0.19	0.11	0.47	0.17	-0.02	0.05	-0.65	0.03	0.29		-0.40		-0.28
1511-1520				-0.27		-0.18	0.22	-0.25	-0.59	0.56	0.36	0.36	0.16	0.34	-0.54	1.28	-0.54	-0.10	-0.19	-1.24	-0.65	-0.85		-0.25		-0.13
1516-1525				-0.40	1.23	-0.41	-0.42	-0.34	-0.89	-0.56	-0.43	0.12	-0.01	-0.05	0.39	0.75	-0.69	0.31	0.19	-1.18	-0.05	-0.01		0.30		-0.19
1521-1530				-1.22	0.13	-0.34	0.09	-0.55	-0.82	-0.45	0.16	-0.16	0.21	-0.09	0.65	-0.07	-0.30	0.93	0.42	-0.49	1.04	0.71		0.75		-0.54
1526-1535			-0.29	-1.75	-0.11	0.11	0.14	0.01	-0.84	-0.40	0.19	0.04	0.29	-0.18	-0.33	0.16	-0.48	0.21	-0.39	-0.49	-0.06	-0.13		0.65		-0.52
1531-1540			-0.25	-1.22	-0.08	0.70	0.31	0.65	-0.65	-0.58	-0.15	0.07	-0.02	-0.10	-0.06	0.36	0.11	1.04	-0.07	0.46	-0.14	0.06		0.41		0.19
1536-1545			-0.07	-0.34	0.57	0.10	0.31	0.16	-0.62	-0.92	-0.20	0.05	-0.58	-0.19	0.05	-0.21	-0.02	1.45	0.46	0.90	0.21	0.22		0.31		-0.19
1541-1550			0.31	1.40	0.58	-0.57	-0.37	-0.17	-0.36	-0.99	-0.24	-0.01	-0.26	-0.28	0.12	-0.83	-0.72	0.50	-0.26	0.30	-0.38	-0.41		0.21	0.21	-0.60
1546-1555			0.78	2.04	0.92	0.18	0.15	0.33	0.46	0.02	0.04	0.10	0.22	0.89	1.05	0.06	-0.09	-0.34	-0.58	0.76	0.14	0.15		0.00	-0.11	-0.26
1551-1560			0.73	0.71	0.37	0.65	0.47	0.54	-0.02	0.76	0.41	0.35	0.04	1.03	1.45	0.61	0.43	-0.48	0.05	1.46	0.19	0.37		-0.73	-0.45	-0.57
1556-1565			0.58	-0.21	-0.53	0.57	-0.22	0.52	-0.07	0.42	0.33	0.76	0.05	0.83	0.84	0.60	0.36	0.37	0.40	1.12	0.47	0.74		-0.85	-0.34	-0.62
1561-1570			0.03	-0.55	0.72	0.53	-0.63	0.37	0.63	0.17	-0.12	0.78	-0.26	0.67	0.04	0.62	0.70	0.34	0.40	0.54	0.33	1.02		-0.36	-0.10	-0.19
1566-1575			-0.52	-1.19	0.42	-0.14	-0.74	-0.28	0.06	-0.21	-0.06	0.77	0.29	-0.26	-0.03	0.27	0.41	0.06	0.26	0.56	-0.18	0.09		-0.06	0.28	0.28
1571-1580			-0.31	-1.10	-0.88	-0.85	-0.83	-0.79	-0.48	-0.71	-0.46	0.19	0.36	-0.69	0.05	-0.58	-0.99	-0.27	-0.29	0.10	-0.72	-0.73		-0.36	0.07	0.69
1576-1585			-0.34	-0.90	-0.98	-0.88	-1.31	-0.94	-0.82	-1.08	-1.36	-0.64	-0.71	-0.84	-0.29	-0.57	-1.12	-0.42	-0.72	-0.49	-1.40	-1.14		-0.66	-0.93	0.05
1581-1590			-0.11	-0.70	-0.44	-0.61	-1.15	-0.78	-0.67	-0.99	-1.45	-0.56	-0.89	-0.78	-0.56	-0.10	-0.27	-0.04	-0.14	-0.08	-1.07	-0.84		-0.07	-0.55	-0.28
1586-1595			0.01	0.54	0.94	-0.44	-0.06	-0.53	-0.03	-0.71	-0.53	-0.75	-0.72	-0.34	-0.44	-0.03	-0.56	-0.31	0.17	0.08	-0.74	-0.66		0.29	0.11	0.12
1591-1600			-0.23	1.11	1.35	-0.33	0.37	-0.35	-0.04	-0.68	-0.25	-0.67	-0.64	-0.13	-0.67	0.06	-0.75	-0.28	0.20	-0.20	-0.60	-0.38		0.26	-0.38	0.40
1596-1605			-0.05	0.20	0.14	0.56	0.22	-0.13	-0.12	-0.06	-0.28	0.05	-0.22	0.59	-0.36	0.38	-0.14	0.17	0.69	-0.08	-0.23	-0.05		-0.24	-0.29	0.63
1601-1610			0.85	-0.21	-0.64	1.00	0.14	0.11	0.45	0.60	0.49	0.04	-0.42	1.28	-0.24	1.02	0.52	0.36	0.63	0.34	0.21	-0.18		-0.47	-0.17	0.15
1606-1615			1.21	-0.26	-0.08	0.40	0.46	0.32	0.48	0.60	0.85	-0.09	-0.72	0.90	-0.23	1.16	0.85	0.48	0.71	1.02	0.85	0.26		0.17	0.12	0.27
1611-1620			0.45	-0.18	1.02	0.20	0.61	0.35	0.77	1.36	0.97	0.40	0.00	1.23	0.21	1.40	0.98	0.34	0.46	0.94	0.97	0.58		0.16	0.72	-0.24
1616-1625			0.01	0.08	0.85	0.20	0.24	0.28	1.22	1.68	0.59	0.51	-0.04	1.15	-0.04	1.28	0.57	-0.36	-0.10	1.67	1.78	1.32		-0.41	-0.12	-1.52
1621-1630			0.36	0.57	0.45	-0.27	0.20	-0.04	0.42	0.43	-0.24	0.03	-0.51	-0.30	-0.28	0.37	-0.33	-1.20	-0.75	1.04	1.34	0.84		-0.77	-0.96	-1.54
1626-1635			-0.17	0.32	0.36	-0.82	0.74	-0.53	-0.22	-0.01	-0.10	-0.00	-0.32	-0.48	0.37	-0.00	-0.76	-1.01	-0.82	-0.94	-0.33	-0.48		-0.42	-0.78	-0.16
1631-1640			0.22	0.32	0.47	-0.69	0.72	-0.39	-0.27	0.12	0.18	0.47	0.17	-0.17	1.47	0.23	-0.99	-0.66	-0.36	-1.09	-0.43	-0.43		-0.22	-0.52	0.29
1636-1645			0.71	0.56	1.60	0.32	0.05	0.66	0.13	0.85	0.13	-0.04	0.17	-0.10	1.56	0.70	-0.24	-0.54	0.29.	0.00	0.40	0.77		0.07	-0.23	-0.28
1641-1650	-0.70		-0.53	-0.23	1.91	0.62	-0.01	0.79	-0.03	1.50	0.44	-0.53	-0.29	0.27	0.99	0.95	0.05	-0.13	0.91	0.48	0.65	0.59		0.24	-0.34	-0.58
1646-1655	-0.48	0.37	-0.77	-0.37	1.66	-0.20	0.42	-0.11	-0.41	0.86	0.77	-0.23	-0.18	0.20	0.29	0.25	-0.46	-0.23	0.47	-0.11	0.10	-0.69		-0.35	-0.28	-0.54

1651-1660	0.17	0.31	−0.11	−0.01	1.21	−0.54	0.32	0.15	−0.16	0.21	0.54	−0.14	0.19	−0.09	−0.12	−0.44	−0.53	−0.47	−0.49	−0.63	−0.15	−1.06	0.38	−0.64	−0.24	−0.07
1656-1665	0.47	−0.37	0.46	0.48	0.63	−0.07	0.23	0.85	0.44	0.25	0.06	0.09	0.10	−0.51	0.39	−0.08	0.17	0.76	−0.80	−0.36	0.03	−1.01	0.21	−0.75	−0.54	−0.14
1661-1670	0.06	−0.47	−0.20	−0.46	−0.28	−0.56	−0.34	−0.00	0.11	0.03	−0.61	−0.28	−0.53	−0.99	0.14	−0.23	−0.22	1.33	−0.36	0.18	0.26	−0.55	−0.42	0.16	−0.57	0.38
1666-1675	−0.45	0.00	−0.96	−0.59	−0.54	−0.74	−0.42	−0.28	0.19	0.06	−0.18	−0.08	−0.45	−0.73	−0.55	−0.61	−1.10	1.10	0.51	0.16	0.34	−0.41	−0.25	1.29	−0.26	0.76
1671-1680	0.13	0.07	−0.86	0.40	0.02	0.06	0.12	0.22	0.84	0.16	0.17	0.51	0.38	−0.33	0.08	−0.14	−0.90	1.09	0.72	0.16	0.53	−0.43	−0.02	0.71	−0.09	0.08
1676-1685	0.57	−0.33	−0.64	0.13	−0.07	0.58	−0.50	0.36	0.37	−0.09	−0.36	−0.14	0.39	−0.31	−0.02	0.18	−0.40	0.85	0.27	0.43	0.57	−0.32	0.11	−0.28	−0.41	−0.71
1681-1690	0.34	−0.46	−0.42	0.04	0.31	0.51	−0.33	0.33	0.12	−0.20	−0.28	−0.84	−0.08	−0.10	−0.62	−0.48	0.15	0.53	−0.09	0.48	0.75	−0.14	−0.18	−0.22	−0.09	−0.71
1686-1695	0.25	0.21	−0.14	0.47	0.64	0.16	0.44	0.31	0.43	−0.04	0.03	−0.82	−0.04	0.03	−0.64	−0.59	−0.16	−0.27	−0.53	−0.07	0.76	0.14	−0.60	−0.23	0.96	−0.34
1691-1700	−0.14	0.40	−0.16	0.10	−0.22	0.39	−0.13	0.41	0.39	−0.13	0.18	−0.40	0.10	−0.02	−0.59	0.03	0.32	−0.26	−0.34	−0.15	0.15	0.14	0.01	−0.42	1.24	0.37
1696-1705	−0.65	0.06	−0.30	−0.34	−0.71	0.34	−0.45	0.33	−0.31	−0.30	0.17	−0.44	−0.01	0.19	0.17	−0.17	0.66	−0.04	0.16	0.14	0.39	0.13	0.61	−0.47	0.13	0.76
1701-1710	−0.79	0.10	−0.39	−0.28	−0.24	−0.36	−0.03	0.15	−0.82	0.05	0.30	−0.63	−0.17	−0.19	−0.04	−0.59	0.11	0.01	0.12	−0.11	0.46	−0.02	0.34	−0.39	−0.59	0.14
1706-1715	−1.14	−0.31	−0.53	−0.19	0.22	−0.48	0.23	−0.03	−0.59	0.18	0.38	−0.41	0.03	−0.14	−1.16	−0.57	0.13	0.33	0.06	−0.39	0.04	−0.08	1.01	0.40	0.03	0.40
1711-1720	−1.11	−0.73	−0.50	0.02	0.39	−0.08	0.12	−0.07	0.39	0.25	0.36	−0.23	0.57	0.74	−0.76	−0.19	0.09	0.43	−0.28	−0.22	−0.04	−0.30	0.91	0.11	0.21	0.30
1716-1725	−0.38	0.04	−0.60	−0.24	0.65	0.13	0.27	−0.15	0.42	0.36	0.56	0.23	0.94	0.85	0.36	0.20	−0.02	0.17	−0.80	−0.30	−0.14	−0.75	−0.43	−0.25	−0.06	−0.22
1721-1730	0.36	0.32	−0.46	0.05	0.42	0.12	0.26	−0.30	−0.21	−0.05	0.34	0.01	0.22	0.84	0.49	0.52	−0.17	−0.20	−0.45	−0.23	0.61	−0.02	−0.31	0.42	−0.28	0.10
1726-1735	0.49	−0.11	−0.17	0.04	−0.36	−0.08	−0.11	−0.34	−0.49	−0.67	−0.14	−0.75	−0.40	0.87	0.17	−0.09	−0.17	−0.57	0.20	−0.37	0.67	0.30	0.31	0.57	−0.24	0.11
1731-1740	0.92	0.35	0.58	−0.46	−0.46	−0.41	−0.47	−0.65	−0.88	−0.64	−0.46	−0.73	−0.43	0.54	−0.04	−0.74	−0.23	−0.42	−0.20	−0.70	−0.10	0.01	−0.16	0.36	0.06	0.05
1736-1745	0.95	0.06	1.21	−0.09	0.30	−0.08	−0.53	−0.40	−0.30	−0.08	−0.39	−0.75	−0.37	0.12	−0.56	−0.11	0.06	0.28	−0.40	−0.38	−0.66	−0.18	−0.90	0.09	−0.35	0.02
1741-1750	0.20	−0.18	1.52	0.38	1.00	0.84	−0.22	0.76	0.56	0.61	0.36	−0.45	0.19	0.63	0.71	0.70	0.83	0.29	0.51	0.52	−0.61	0.28	0.05	0.02	−0.51	−0.48
1746-1755	0.09	−0.32	0.94	−0.16	0.59	0.14	−0.20	0.00	−0.15	0.40	0.31	0.10	0.46	0.58	1.29	0.26	0.86	0.07	0.80	0.66	−0.24	0.39	1.32	0.04	−0.06	0.06
1751-1760	0.85	−0.64	0.33	−0.37	0.26	−0.82	−0.31	−0.87	−0.24	−0.20	−0.43	0.32	0.47	−0.07	−0.14	−0.19	−0.23	−0.27	−0.17	−0.49	−0.76	−0.75	0.50	−0.21	−0.47	0.33
1756-1765	1.19	0.01	0.80	0.13	0.33	−0.54	−0.05	−0.45	0.50	0.00	−0.50	0.16	0.51	0.24	0.05	−0.00	−0.69	−0.61	−0.35	−0.35	−0.31	−0.66	−0.19	−0.29	−0.49	0.44
1761-1770	0.97	0.86	0.84	0.41	0.27	0.11	0.54	0.19	0.33	0.26	−0.09	0.11	0.33	0.40	0.75	0.35	−0.13	−0.39	0.18	0.20	0.62	0.23	−0.13	−0.12	0.31	0.95
1766-1775	−0.00	0.68	0.44	0.28	−0.03	0.53	0.32	0.62	−0.12	0.00	−0.14	0.33	0.09	−0.07	0.59	0.66	0.22	−0.16	0.24	0.19	0.63	0.79	0.08	−0.24	−0.07	0.01
1771-1780	−1.15	−0.16	0.10	−0.52	−0.13	−0.08	−0.23	−0.16	−0.68	−0.55	−0.58	−0.12	−0.53	−0.72	0.04	0.23	−0.33	−1.13	−0.17	0.25	0.69	1.23	0.04	−0.05	−0.45	−0.69
1776-1785	−0.74	−0.48	0.02	−0.45	0.16	−0.44	−0.15	−0.69	−0.70	−0.64	−0.49	−0.27	−0.55	−0.63	−0.03	−0.61	−0.83	−1.96	−0.84	−0.25	−0.03	0.26	−0.81	0.29	0.09	−0.41
1781-1790	−0.52	−0.75	−0.29	−0.30	−0.04	0.09	−0.24	−0.13	−0.32	−0.59	−0.47	−0.05	−0.15	0.42	0.32	−0.79	−0.05	−1.47	−0.32	−0.10	−0.48	−0.18	−0.98	0.63	0.83	0.27
1786-1795	−0.31	−0.20	0.08	−0.04	0.19	0.58	0.12	0.54	0.62	−0.34	−0.20	−0.21	0.04	−0.13	0.82	−0.36	0.25	−0.64	0.83	0.15	−0.31	0.24	−0.73	−0.11	0.27	0.14
1791-1800	−0.20	0.48	0.39	0.06	0.07	0.54	0.47	0.32	0.70	0.16	0.06	0.02	0.51	0.09	1.02	0.21	−0.18	−0.22	0.27	−0.57	−0.98	−0.23	−0.57	−0.90	−0.77	−0.74
1796-1805	−0.79	−0.04	0.16	−0.04	0.03	0.60	−0.15	0.08	−0.38	0.12	−0.04	0.13	−0.03	−0.01	0.40	0.80	0.17	0.47	−0.34	−0.32	−1.01	−0.54	−0.21	−0.45	−0.20	−0.63
1801-1810	−0.66	−0.45	0.34	0.03	0.68	0.30	−0.47	−0.41	−0.47	−0.48	−0.20	−0.21	−0.65	−0.16	−0.46	0.46	0.13	1.40	0.64	0.28	−0.58	−0.61	0.37	−0.20	0.59	−0.32
1806-1815	0.34	−0.48	1.02	0.02	0.64	−0.46	−0.07	−0.87	−0.19	−0.73	−0.35	−0.28	−0.18	−0.18	−0.51	−0.28	−0.21	1.32	1.06	0.11	−0.35	−0.44	1.14	−0.52	0.47	−0.11
1811-1820	0.83	−0.26	0.86	0.02	0.40	−0.17	−0.13	−0.17	−0.45	−0.70	−0.27	0.21	0.13	0.20	−0.18	−0.27	0.20	1.13	0.81	0.13	−0.17	−0.47	1.49	−0.56	0.74	0.40
1816-1825	−0.38	0.19	0.07	−0.52	−0.08	−0.11	−0.76	−0.22	−0.66	−0.63	−0.37	0.65	−0.24	−0.15	0.08	−0.28	−0.41	0.46	0.53	0.38	−0.63	−0.27	0.49	−0.18	1.14	0.44
1821-1830	−1.30	1.26	0.62	−0.09	0.12	−0.05	−0.07	−0.12	0.14	−0.01	−0.18	0.60	−0.05	−0.45	0.19	−0.37	−0.70	−0.12	0.10	1.13	−0.48	0.70	−0.28	0.78	0.79	0.55
1826-1835	−0.30	1.32	0.93	0.73	0.24	0.64	0.80	0.47	0.86	0.61	0.35	0.93	0.38	−0.11	−0.08	−0.23	−0.38	−0.14	−0.39	1.20	−0.08	1.00	0.05	0.73	0.38	0.26
1831-1840	0.84	0.61	0.49	0.82	−0.33	0.93	0.85	0.62	0.71	1.01	0.86	1.19	0.38	0.23	0.73	−0.19	−0.60	−0.13	−0.10	0.66	−0.05	1.10	0.11	0.23	0.16	−0.09
1836-1845	0.76	0.47	0.08	0.13	−0.46	0.01	0.26	−0.28	0.06	0.56	0.81	1.20	0.17	0.39	0.85	−0.43	−0.90	−0.43	−0.50	−0.04	0.10	0.75	−0.25	−0.06	−0.24	−0.63
1841-1850	0.13	0.40	−0.38	−0.16	−0.36	−0.77	−0.43	−0.70	−0.64	0.13	0.42	0.85	−0.27	0.35	−0.24	−0.49	−0.93	−0.62	−1.57	−1.00	−0.48	−0.42	−0.35	−0.60	−0.30	−0.89
1846-1855	−0.15	0.13	−0.34	−0.02	−0.52	0.37	−0.38	0.33	−0.22	0.33	0.30	−0.07	−0.70	0.54	−0.56	0.06	−0.20	0.07	−0.68	−0.60	−0.48	−0.39	−0.26	−0.30	−0.14	−0.37
1851-1860	−0.15	−0.08	−0.04	0.27	−0.65	0.13	0.10	−0.26	−0.14	0.14	0.32	−0.07	−0.65	0.26	−0.23	−0.37	−0.51	0.08	0.21	−0.33	−0.38	−0.15	0.05	−0.12	−0.52	−0.38
1856-1865	−0.18	−0.16	−0.10	−0.19	−0.82	−0.74	−0.39	−0.84	−0.52	−0.17	−0.07	−0.28	−0.43	−0.21	0.12	−0.66	−0.92	−0.32	0.14	−0.58	−1.02	−0.79	0.40	−0.46	−0.92	−0.16
1861-1870	−0.44	−0.31	−0.31	−0.35	−0.88	0.08	−0.28	0.28	0.43	0.05	0.04	−0.22	0.25	0.12	0.51	0.35	0.26	−0.02	0.48	−0.07	−0.51	−0.73	0.00	−0.73	−0.87	0.08
1866-1875	−0.43	−0.37	−0.78	−0.03	−0.72	0.00	0.33	0.44	0.43	−0.05	−0.11	0.22	0.13	−0.03	0.12	0.70	1.10	−0.19	0.27	−0.18	0.21	−0.27	−0.77	−0.34	−0.13	−0.09
1871-1880	−0.02	−0.55	−0.78	−0.31	−0.87	−0.58	−0.20	−0.39	−0.84	−0.15	−0.57	0.17	−0.55	−0.62	−0.27	0.02	1.01	−0.46	0.07	−0.35	0.30	0.35	−0.24	0.16	0.67	0.24
1876-1885	0.40	−0.06	−0.27	0.15	−0.61	−0.46	−0.04	−0.62	−1.08	−0.24	−0.33	0.14	−0.27	−0.66	−0.15	−0.18	0.67	−0.02	0.16	0.16	0.14	0.98	0.46	0.15	0.87	0.89
1881-1890	0.28	−0.07	−0.14	0.10	−0.28	0.15	0.39	−0.17	−0.40	−0.17	0.06	0.00	−0.38	−0.48	−0.92	0.31	0.24	−0.20	−0.34	−0.18	−0.16	0.70	−0.24	0.02	0.63	0.45
1886-1895	−0.28	−0.59	−0.58	−0.49	−0.63	0.66	0.10	0.63	0.42	0.22	0.02	0.11	−0.18	−0.33	−0.99	0.53	0.56	−0.58	−0.35	−0.48	0.01	0.23	−0.75	−0.17	0.41	−0.41
1891-1900	−0.24	−0.65	−0.45	−0.34	−0.75	−0.34	−0.29	0.02	0.04	−0.23	−0.65	0.07	0.08	−0.44	−0.24	0.12	0.72	−0.16	−0.03	−0.26	0.06	0.01	−0.71	0.26	−0.00	−0.38
1896-1905	−0.02	−0.19	−0.37	−0.34	−0.54	−0.99	−0.56	−0.83	−0.90	−0.84	−0.83	−0.17	−0.19	−0.54	−0.36	0.20	0.42	0.16	0.09	−0.10	−0.22	−0.33	−0.30	1.38	−0.16	−0.01
1901-1910	−0.10	0.28	−0.28	0.06	−0.22	0.16	−0.11	0.10	−0.02	−0.19	−0.16	−0.16	−0.11	−0.08	−0.46	0.82	0.81	0.54	1.01	0.39	0.44	0.07	0.34	1.00	0.03	0.04
1906-1915	0.51	0.39	0.01	0.84	0.15	0.59	0.73	0.87	0.97	1.16	0.58	0.37	0.53	0.69	0.10	1.18	0.89	0.35	1.15	1.42	1.40	1.18	0.63	0.23	−0.12	0.07
1911-1920	0.75	0.34	−0.30	0.92	0.57	0.32	1.11	0.84	1.51	1.22	0.93	0.47	0.77	0.76	0.31	1.38	0.85	−0.27	−0.22	1.02	1.04	1.24	−0.01	0.30	−0.49	0.04
1916-1925	−0.01	0.09	−0.25	0.03	0.20	0.31	0.51	0.58	1.68	0.82	0.66	−0.19	0.34	0.67	0.27	1.08	0.28	−0.35	−1.18	−0.10	0.57	0.39	−0.76	−0.37	−0.69	−0.60
1921-1930	−0.07	−0.08	0.02	−0.47	0.22	0.03	0.29	0.21	0.70	0.29	0.19	−0.30	0.07	0.67	0.82	0.53	−0.78	−0.56	−1.23	0.14	0.29	−0.16	−1.18	−0.61	−0.20	−0.85
1926-1935	0.20	−0.15	0.58	0.01	1.34	−0.29			0.31	−0.29	−0.14	0.17	−0.17	0.08	0.70	−0.05	−1.20			−0.72	−0.45	−0.67	−1.58	−0.20	0.26	−0.63
1931-1940	−0.52	−0.00	0.51	−0.31	1.46	0.28			0.00	−0.83	−0.42	−0.06	−0.34	−0.18	−0.27	−0.13	−0.77			−1.34	−0.90	−1.11	−1.21	−0.53	−0.38	−0.14
1936-1945		−0.01	0.59	−0.44	1.31	0.92			0.20	−1.11	0.01	−0.23		0.44	−0.49	−0.08				−0.81	−0.23	−0.50		−0.62	−0.61	
1941-1950			1.18	−0.76	0.52	0.02			0.52	−1.06		0.70				−0.39				−0.47	0.92	0.21		−0.28		
1946-1955			1.25		−0.47				−0.26	−1.31																
1951-1960			1.35		−0.42				−0.80																	

A.D., so this 270-yr. period was chosen as a "standard" interval. The mean and the standard deviation for the indices in each chronology were calculated for this "standard" interval. Then, for the entire length of each chronology, mean indices were calculated for 10-yr. periods starting with the year 1 and 6 of each decade. Because of the lag in the response of growth to climate, it is thought that the tree growth interval starting with the year 1 corresponds most closely to the climate of the usual decades which begin with the year ending in a zero.

Each 10-yr. mean is converted to a relative departure by subtracting the mean and dividing by the standard deviation of the chronology during the 270-yr. "standard" interval. This subtraction and division largely correct for differences in the variability and means of the 26 series, but do not eliminate the influence of serial correlation. As a result, the 10-yr. relative departures sometimes appear overestimated in those series which exhibit the highest serial correlations.

The relative departures for the 26 chronologies are presented in table 8. The data for the interval 1501 through 1940 were plotted on maps, and lines of equal values were drawn through positive and negative departures of 0.2, 0.6, 1.0, 1.4, and 1.8. Care was taken to draw lines based exclusively on the data and smoothing was avoided except in cases where wide discrepancies occur among chronologies in close proximity (numbers 6 and 8, 12 and 22, and 18 and 25). In such cases, lines were drawn according to the mean for the two departures. The series of maps showing chronology location and the lines of equal departure are presented in figures 2–10.

The areas with a positive growth departure exceeding 0.6 are shaded with vertical lines. The areas with a negative growth departure exceeding 0.6 are shaded with dots. In the following discussion, conditions of high precipitation and low temperatures are inferred from positive growth departures and are referred to as moist climates. Conditions of low precipitation and high temperatures are inferred from negative growth departures and are referred to as dry climates.

Random error or statistical noise is unavoidable in such an analysis, especially in the earliest portions of certain chronologies. This error creates discrepancies in individual chronologies and should not be considered as climatically significant. For example, a period such as 1786–1795, which exhibits numerous small high and low growth areas, provides little information on the regional climate. However, most of the maps show large areas of similar departure and gradual changes over great distances. These major regional similarities and changes are most probably a result of similarities and changes in climate.

Figure 2 contains maps for the first half of the 16th century, a period characterized by the persistence of dry conditions centering in the Colorado River Basin but by alternating wet and dry conditions to the north.

1501–1515: Moisture is below average in the Intermountain area but above average to the south.

1511–1525: Dry conditions occur farther east, centering in the north-central Rockies and the Colorado River Basin.

1521–1530: Dry conditions intensify in the Southwest, and the Northwest becomes moist.

1526–1535: The Lower Colorado continues to be extremely dry, and the Northwest and Intermountain areas become dry.

1531–1550: The central Pacific and northern Rockies become moist; the Colorado River Basin remains dry.

1541–1555: The prolonged dry climate in the Colorado River Basin is finally broken by moist conditions developing in areas along the Mexican border and the central Rocky Mountains. The Northwest becomes dry.

The maps in figure 3 show the last half of the 16th century, which was a period with extensive areas of wet and dry extremes.

1551–1565: Moist conditions intensify in the north-central Rockies while the climate of the Rio Grande Basin and Canada become dryer.

1561–1570: The area from the Colorado River to the Canadian border and the eastern slope of the southern Rocky Mountains becomes more moist, while the Upper Rio Grande Basin becomes dry.

1566–1585: Dry conditions intensify in the Southwest and northern Rockies; a major drought develops until it finally extends throughout the entire West.

1581–1605: Dry conditions become more restricted to the Rocky Mountain areas as moist conditions develop in the Rio Grande and Gila River Basins and in the Northwest.

Figure 4 contains maps for the first half of the 17th century, which was also a period with extensive areas of moist and dry extremes.

1601–1625: An extensive, extremely moist climate expands throughout the central portions of the West.

1616–1635: A dry climate develops in Canada and the Pacific Northwest and gradually spreads southward as the area of moist climate moves northeastward.

1631–1645: Moist conditions which persist in the eastern and southern Rocky Mountain areas begin to intensify and expand as dry conditions to the west diminish.

1641–1650: Moist conditions intensify in the Rio Grande and Upper Colorado River Basins, expand into the southern and north-central portions of the West, but do not reach their previous maximum extent.

1646–1655: The extreme conditions which prevailed over western North America for a century become more localized and confined to the Southwest.

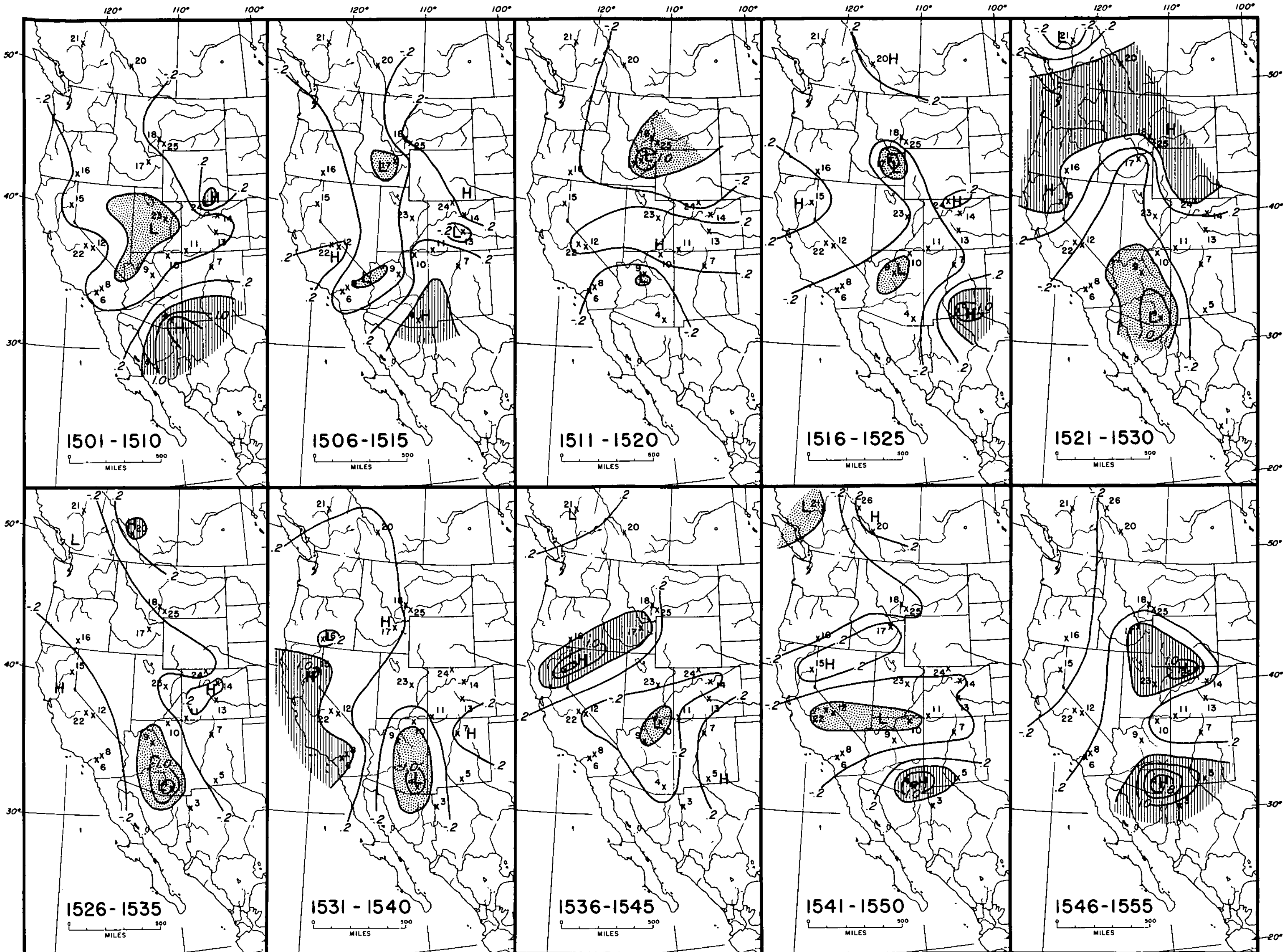

FIGURE 2.—Maps of regional variations in climate based upon 10-yr. relative departures in tree-ring indices from western North America (table 8). Positive departures indicate moist cool areas, and negative departures indicate dry and warm areas. Symbols H and L designate centers of high and low growth. Areas are shaded when departures exceed 0.6. Station locations are omitted where data are not available.

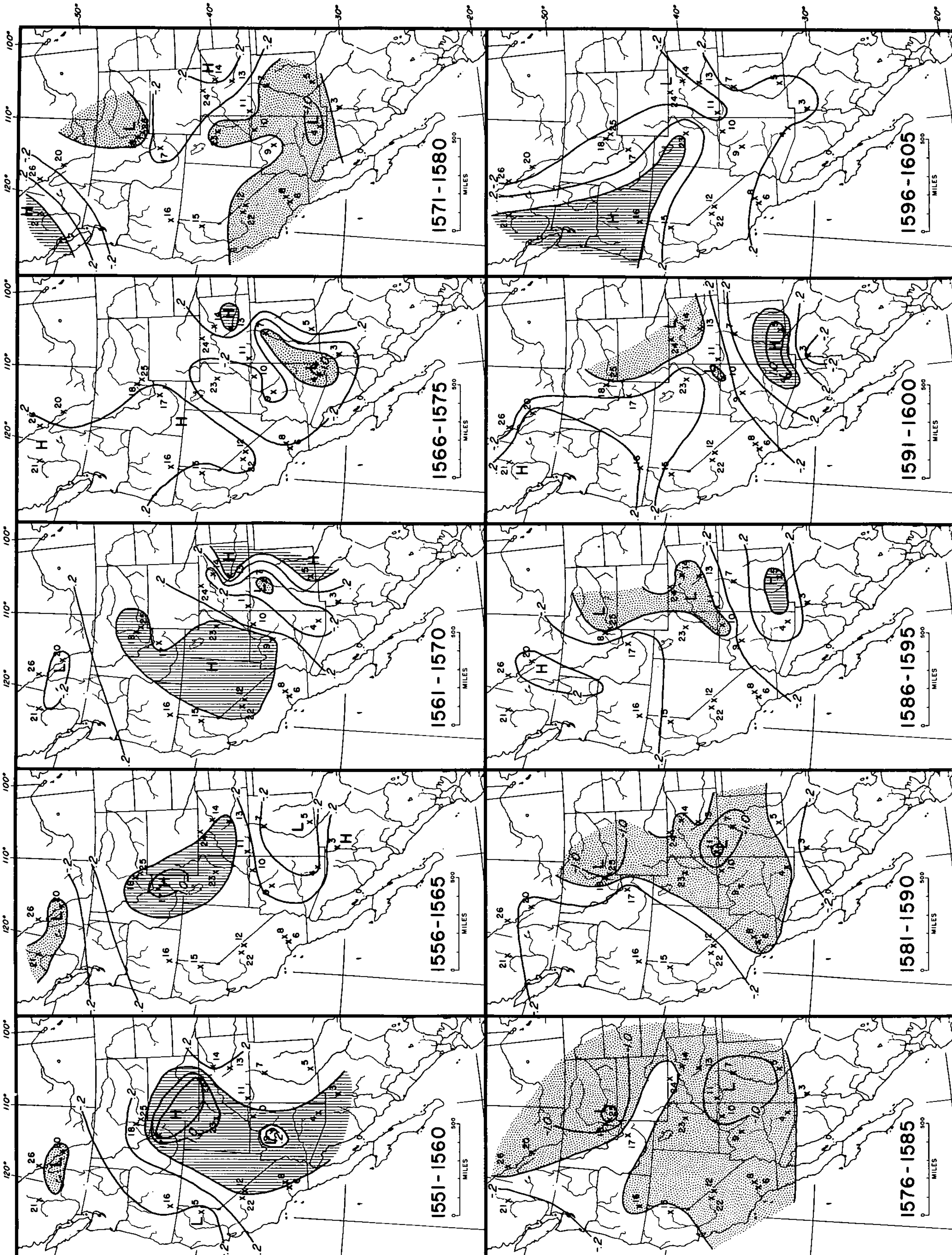

FIGURE 3.—Maps of regional variations in climate. See legend to figure 2.

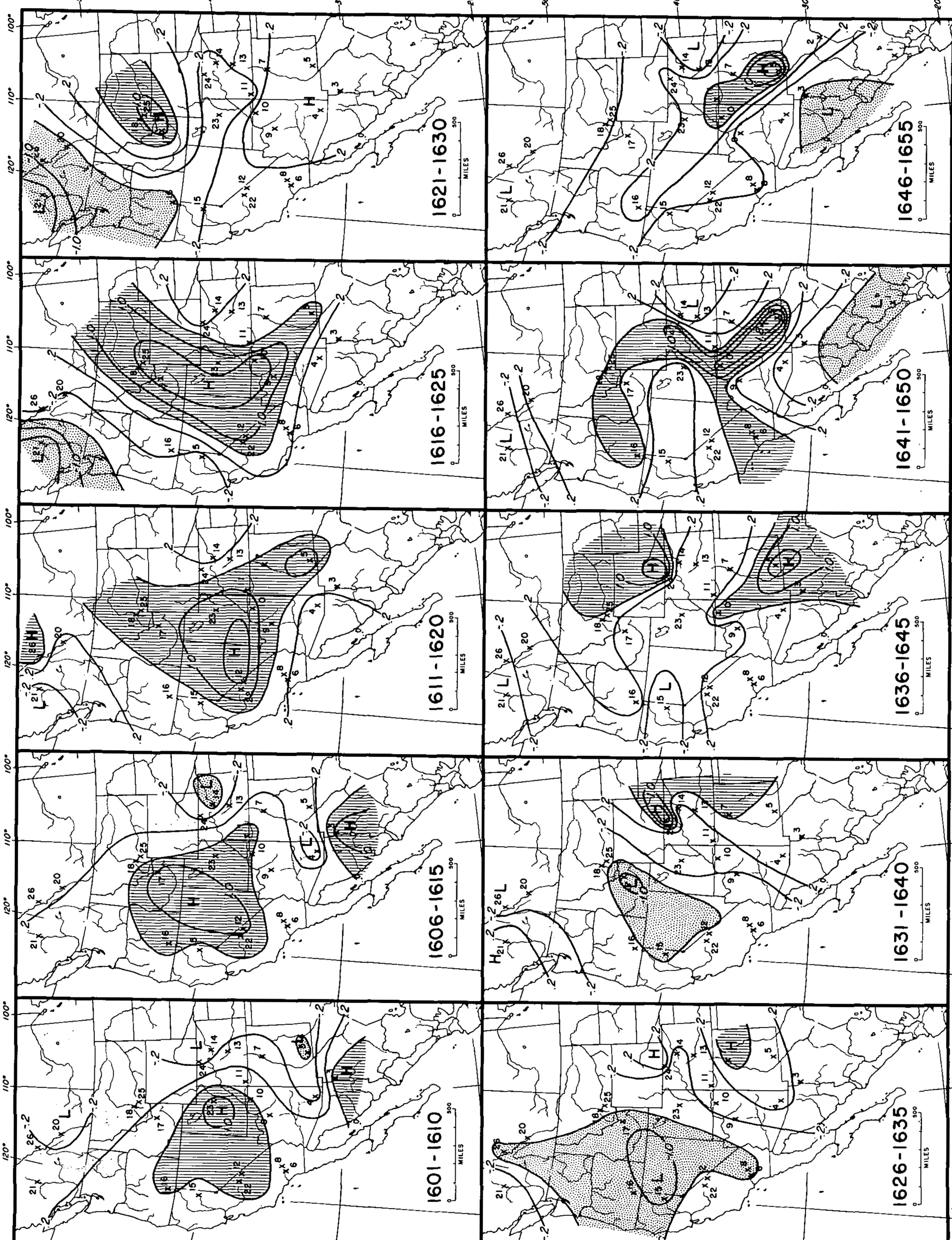

FIGURE 4.—Maps of regional variations in climate. See legend to figure 2.

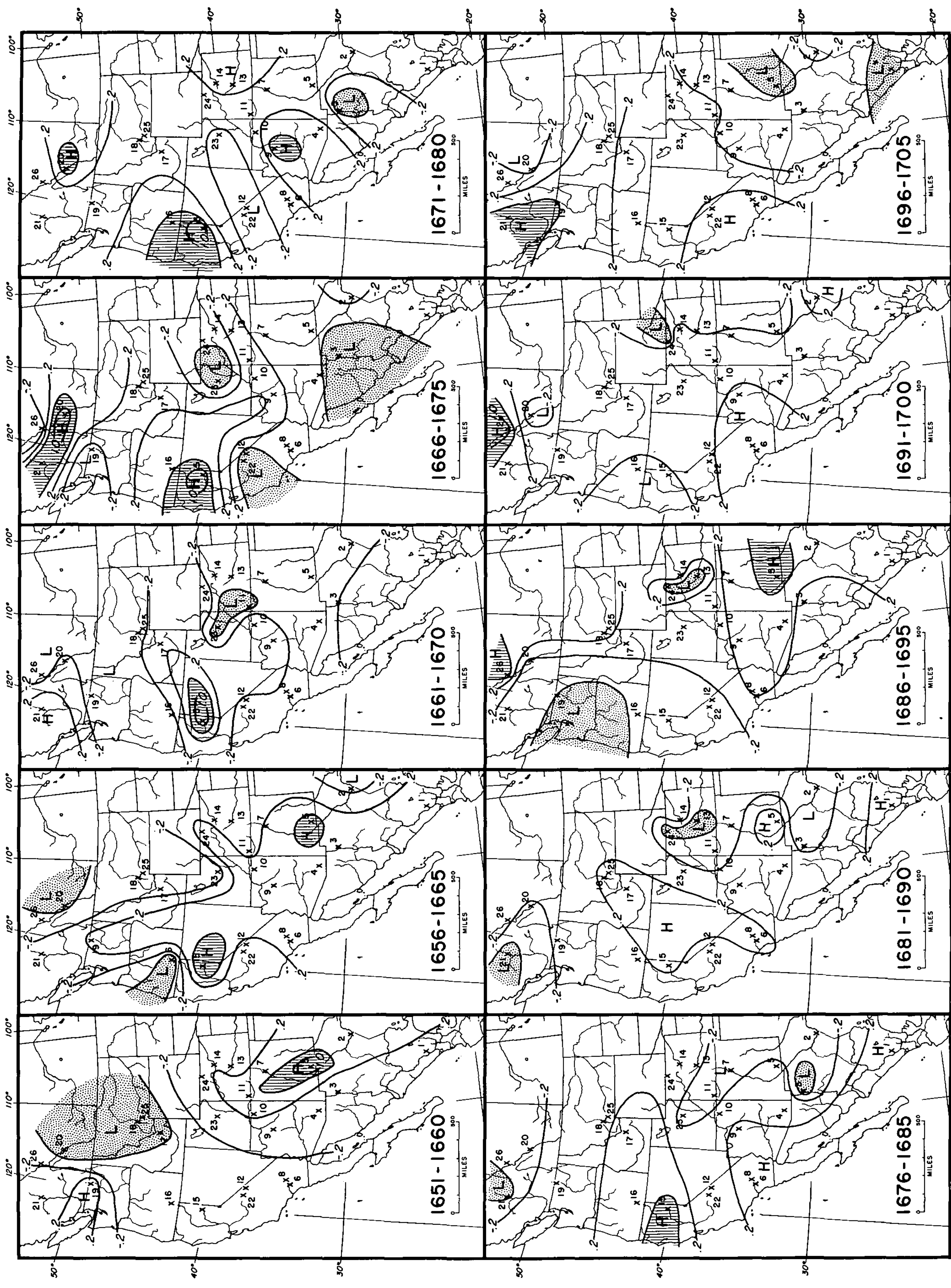

FIGURE 5.—Maps of regional variations in climate. See legend to figure 2.

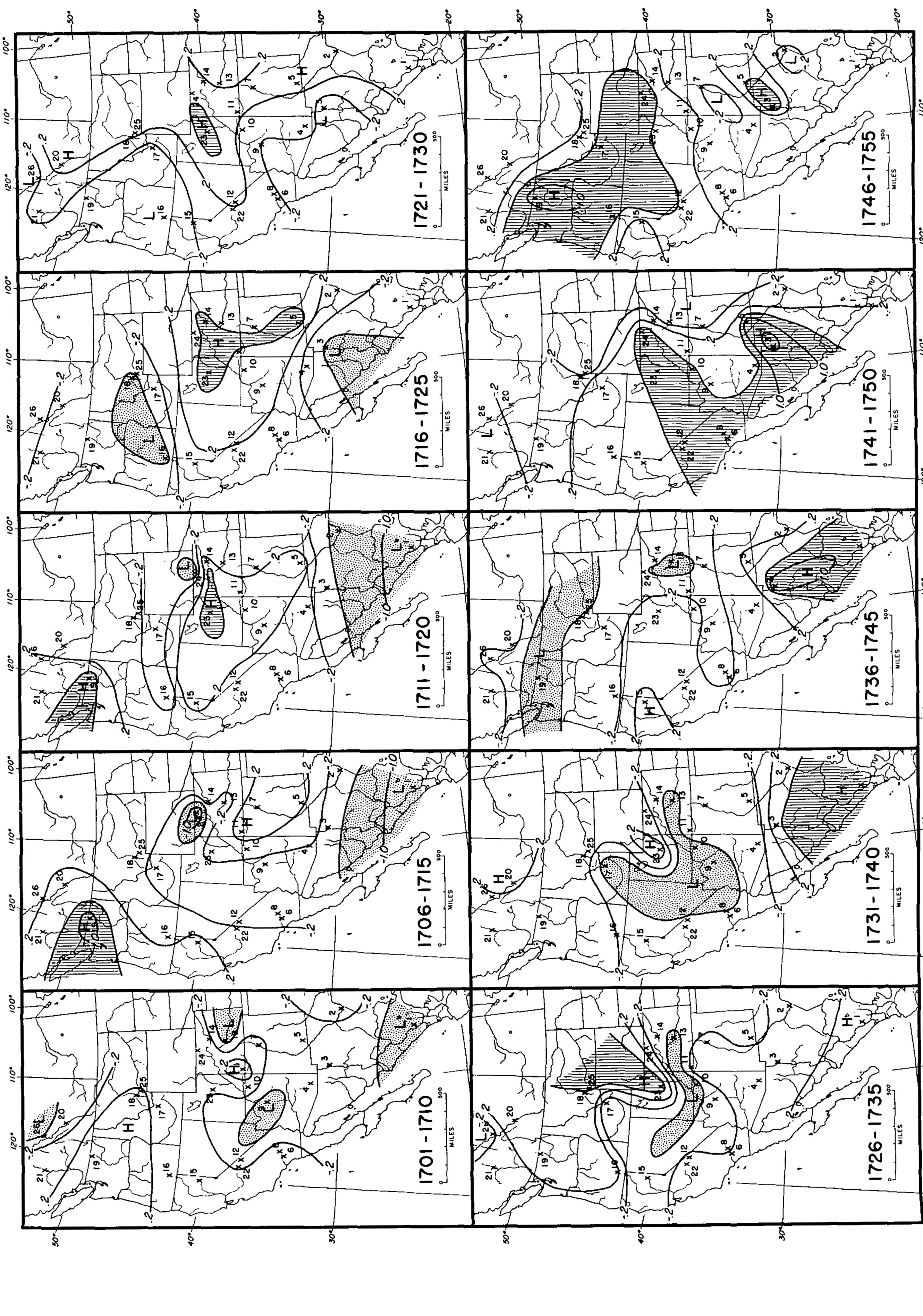

FIGURE 6.—Maps of regional variations in climate. See legend to figure 2.

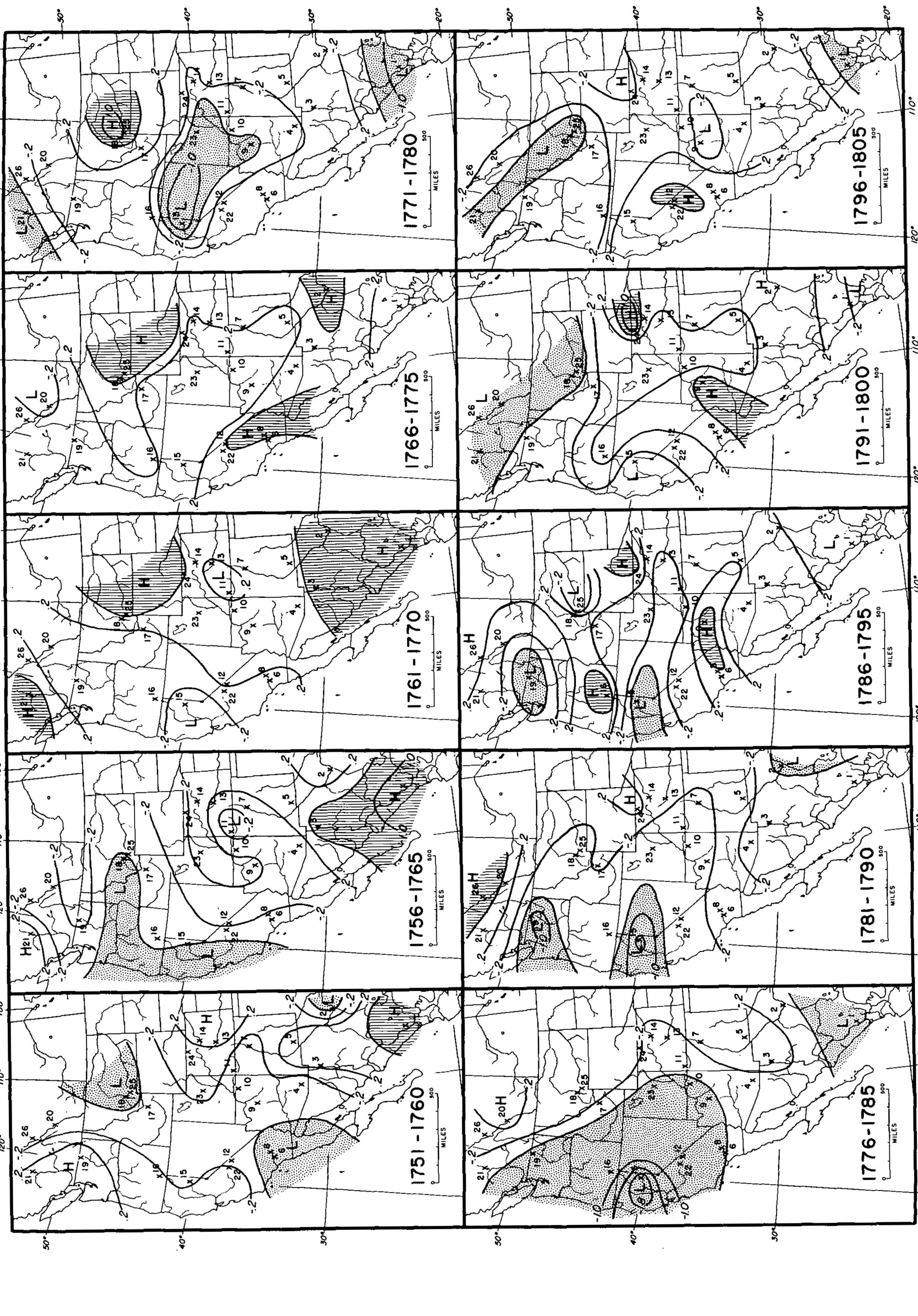

FIGURE 7.—Maps of regional variations in climate. See legend to figure 2.

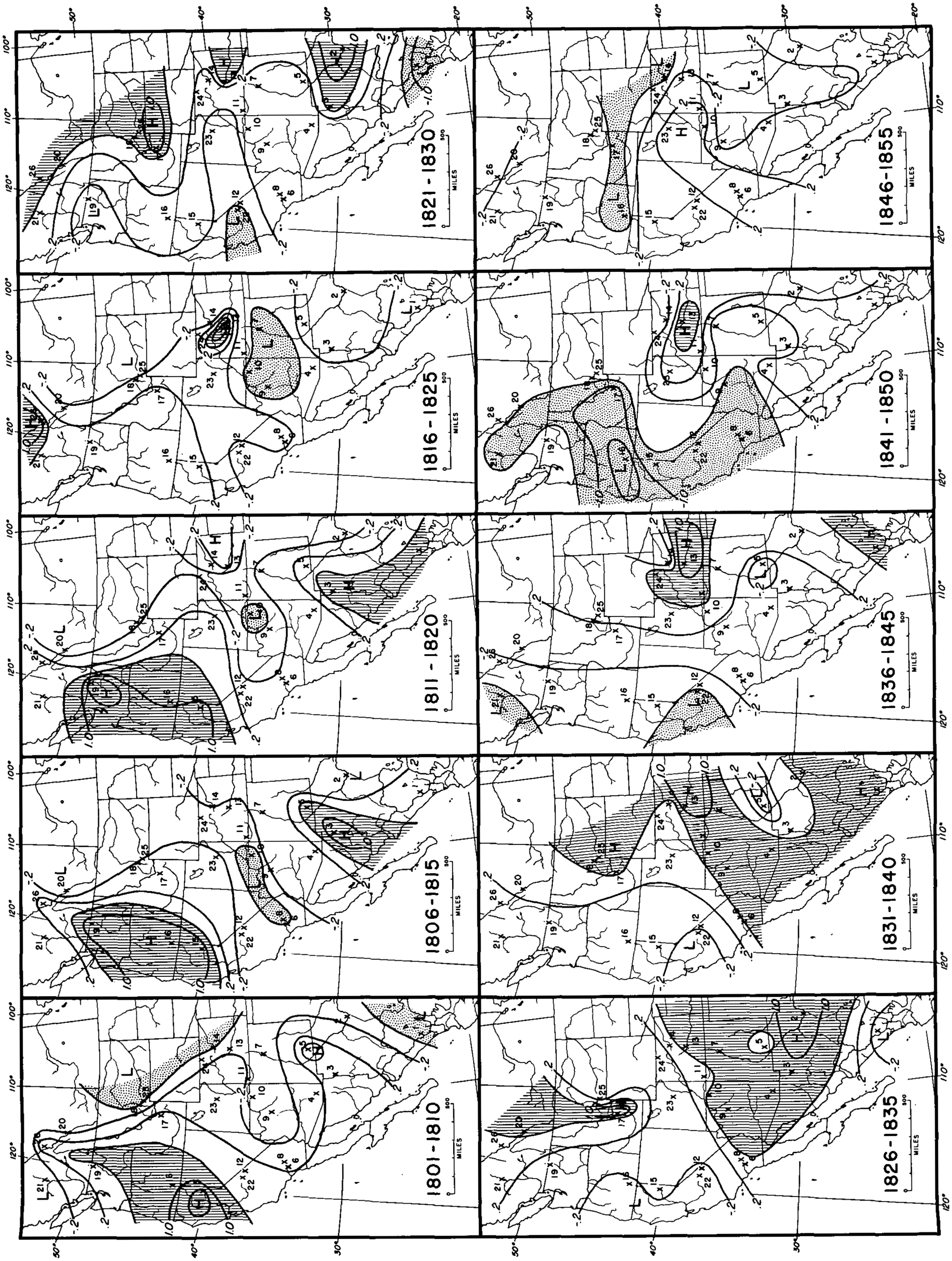

FIGURE 8.—Maps of regional variations in climate. See legend to figure 2.

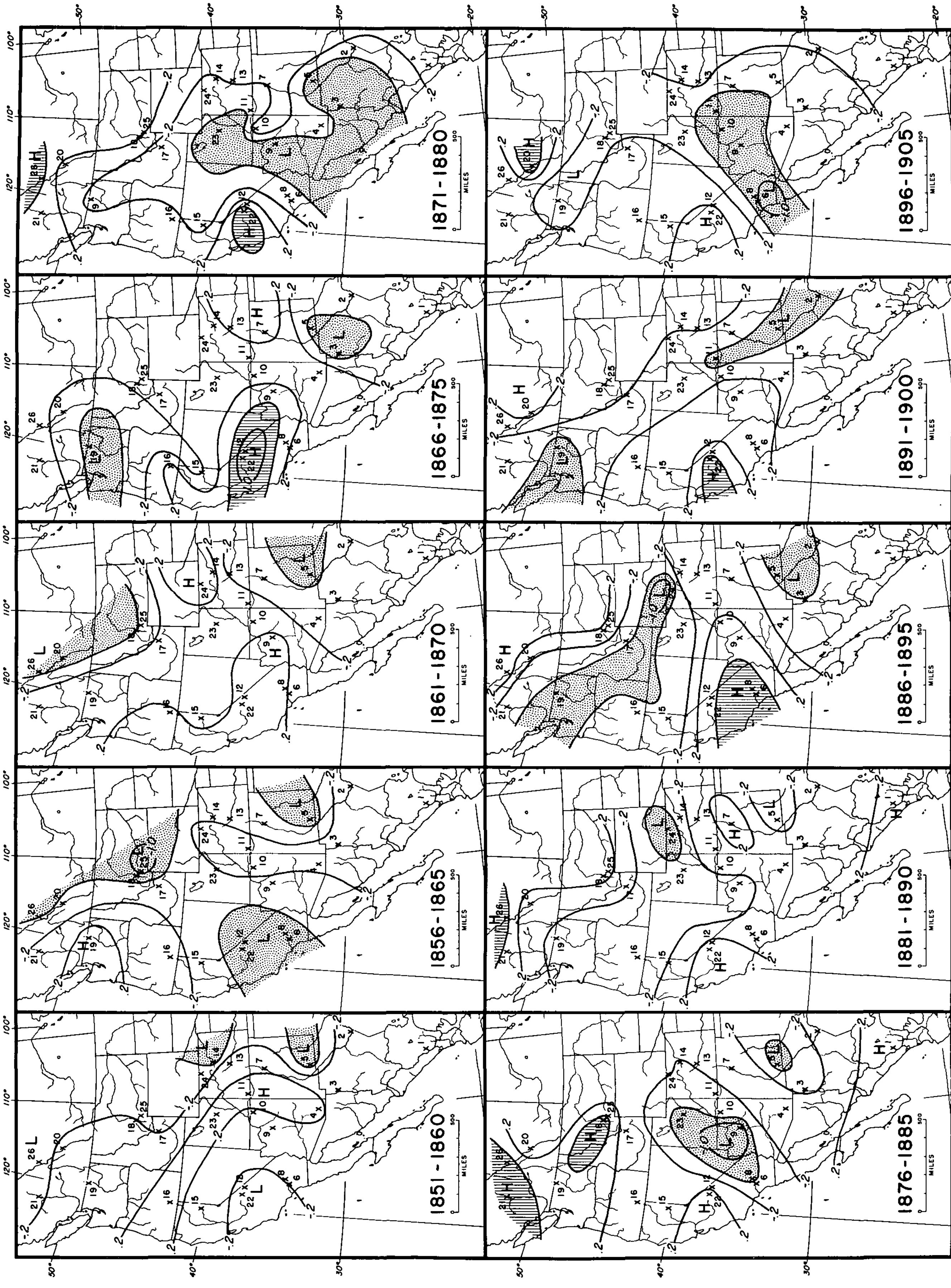

FIGURE 9.—Maps of regional variations in climate. See legend to figure 2.

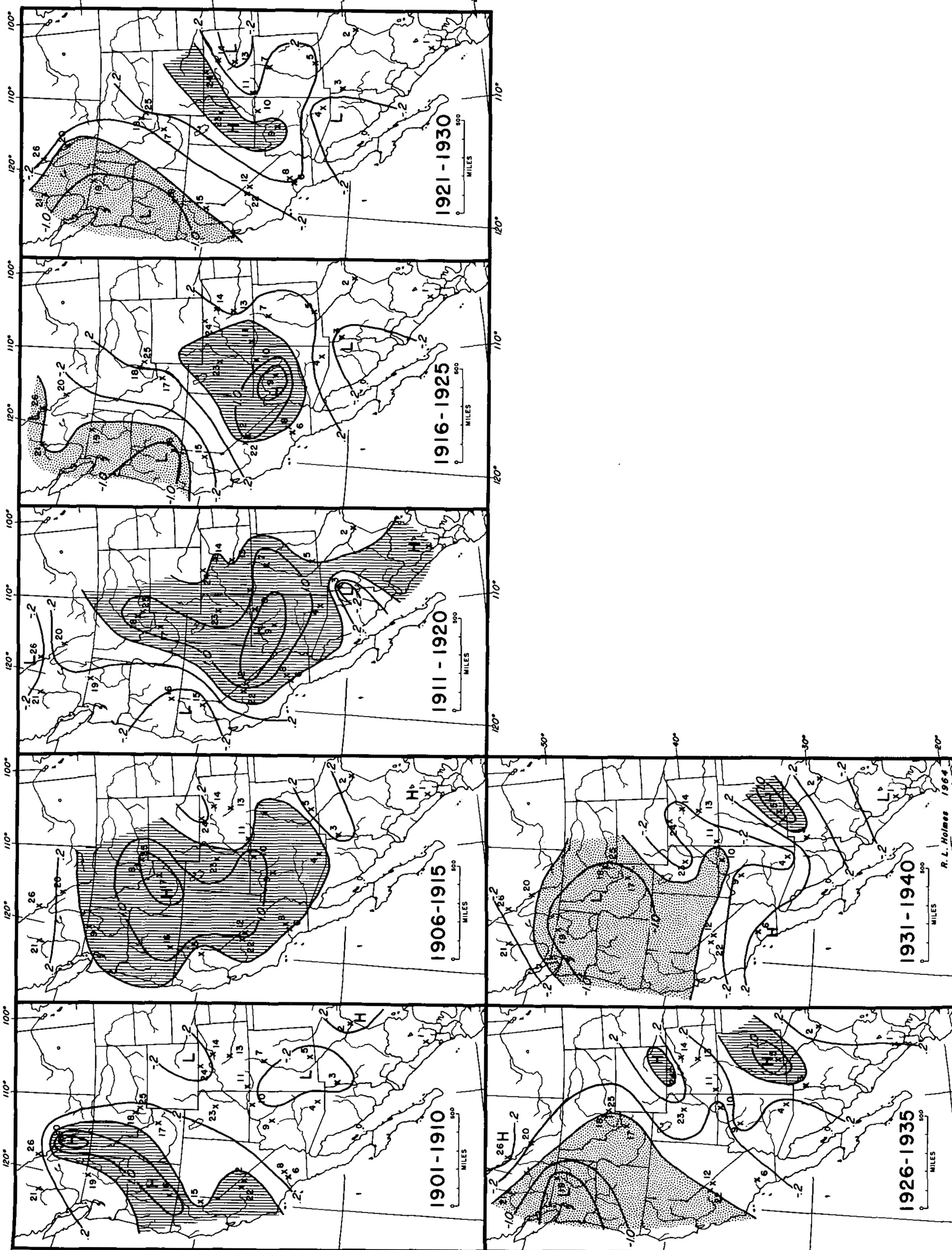

FIGURE 10.—Maps of regional variations in climate. See legend to figure 2.

Figure 5 covers the last half of the 17th century, a period exhibiting little climatic change.

1651–1660: Moisture is above average in the Rio Grande Basin and dry conditions prevail over the northern Rockies.

1656–1690: Northern California, southern Oregon, and southern Idaho receive above average moisture but the Upper Colorado River Basin is generally dry. In other areas only local changes of short duration occur.

1686–1705: The climate of the Northwest is first dry but becomes wet while in the extreme Southwest the climate is first wet, then becomes dry. Below average moisture conditions persist in the Upper Colorado River Basin and central Rocky Mountains.

Figure 6 includes maps for the first half of the 18th century, a period initially exhibiting little climatic change. Later, more extreme conditions developed.

1701–1715: Above average moisture continues in the Northwest. The Southwest is somewhat dry.

1711–1730: A moist climate in the Upper Rio Grande Basin expands into the central Rocky Mountains, while the Northwest becomes dry.

1726–1740: Moist conditions move farther north into the Rocky Mountains as dry conditions intensify in the Southwest.

1736–1755: Dry conditions occur along the Canadian border and in the central Rockies, but are replaced by an extensive moist climate which moves from south to north.

The maps in figure 7 cover the last half of the 18th century, which was a period exhibiting complex patterns of moist and dry conditions.

1751–1760: Dry conditions develop in southern California and the northern Rockies.

1756–1765: The entire Pacific Coast becomes dry, while Mexico is moist.

1761–1775: The climate of the West becomes more moist, especially in areas along the Mexican border and in the northern Rockies.

1771–1790: Dry conditions developing in northern California and the Great Basin cover the area west of the Rocky Mountains.

1786–1805: Dry conditions move to the Pacific Northwest and extend into the Canadian and northern Rocky Mountains. The climate of California and the Colorado River Basin becomes more moist.

Figure 8 covers the first half of the 19th century, a period of more persistent and extensive climatic change.

1801–1820: The Pacific Northwest and northern Mexico become moist; the northern Rockies and the Colorado River Basin become dry.

1816–1830: Dry conditions persist in California and the Southwest, the climate of the Pacific Northwest becomes more average, and areas of the Rocky and Sierra Madre Mountains become moist.

1826–1841: The Rocky Mountains, the Southwest, and Mexico become moist.

1836–1850: Dry conditions develop over the Pacific Coast and expand throughout the Far West. Moist conditions persist in the Upper Colorado River Basin and in the central Rockies.

Figure 9 includes maps for the last half of the 19th century, which was a period of fluctuating but below average moisture.

1851–1865: Dry conditions intensify in California and throughout the Rocky Mountain chain.

1861–1875: California becomes moist but the Canadian and Mexican border regions remain dry.

1871–1880: Dry conditions prevail east of the Sierra Nevada and the Cascade Mountains and throughout the Rocky Mountain Range, but central California and the Canadian Rockies are moist.

1876–1890: The Colorado River and central Rio Grande Basins are dry. The Canadian Rockies remain moist.

1886–1900: Southern California and the Lower Colorado River Basin become moist, and dry conditions intensify in the Rio Grande Basin and extend northward from the Upper Colorado to the Pacific Northwest.

1896–1905: Dry conditions return to the Colorado River Basin; the Southwest and Rocky Mountain areas are generally dry.

The maps in figure 10 span the first 40 years of the 20th century, a period starting with abundant moisture and ending with a widespread drought.

1901–1910: The Pacific Coast and northern Rockies become moist.

1906–1915: Extremely moist conditions prevail throughout western North America.

1911–1935: Drier conditions develop in the Pacific Northwest, intensify, and move southwestward as the area of extreme moist climate diminishes.

1931–1940: Extremely dry conditions extend throughout the West except for the area of southern New Mexico and Chihuahua.

These maps represent a tentative reconstruction of the patterns in climate during the past four and a half centuries. As new and better data are added the maps will undoubtedly be revised. The author has outlined his methods and results which employ only dendroclimatic and botanical techniques. Verification from other lines of evidence should also be considered. A preliminary search of these sources indicates more agreement than disagreement. However, many of these data are qualitative and difficult to evaluate in terms of the precisely dated chronologies derived from tree rings.

The maps represent only a modest beginning of dendroclimatic investigation. More stations must be sampled and incorporated in the present study, and earlier time periods should be analyzed. However, there are fewer chronologies during these early periods and errors may be greater, for fewer specimens are available and these specimens are likely to be relatively short archaeological pieces. Because of these difficulties, mapping of the climate prior to the 16th century was not attempted. However, plots and comparisons of the early data show climatic variations comparable to those mapped in figures 2–10.

It is hoped that this kind of investigation will provide a basis for relating the short periods of recorded weather to climatic patterns of the past as well as provide clues to the nature and causes of climatic change. It is reasonable to infer that this type of analysis may be applied to other arid or cold areas of the world. A series of such analyses on a global scale would provide highly valuable regional information on long-term fluctuations in atmospheric circulation and on possible factors influencing the heat balance and water economy of marginal lands.

ACKNOWLEDGMENTS

This work was supported by the U.S. Weather Bureau, contract Cwv–10798. The analyses of the tree-growth relationships were also sponsored by the National Geographic Society and the U.S. Department of Interior, National Park Service, through the Wetherill Mesa Archaeological Project. The author acknowledges the able assistance of David G. Smith and Richard L. Holmes. He is also indebted to past and present staff at the Laboratory of Tree-Ring Research for the development of the regional tree-ring chronologies, and to the Numerical Analysis Laboratory, The University of Arizona, for free computing time and services. He wishes to express his appreciation for the help of James A. Erdman, Maurice E. Cooley, and Julie McMahan, who contributed to various phases of the project.

REFERENCES

1. H. S. Colton, "Precipitation about the San Francisco Peaks, Arizona," *Museum of Northern Arizona Technical Series*, No. 2, 1958, 18 pp.
2. A. E. Douglass, "Photographic Tree-Ring Chronologies and the Flagstaff Sequence," *Tree-Ring Bulletin*, vol. 14, No. 2, 1947, pp. 10–16.
3. H. C. Fritts, "An Approach to Dendroclimatology: Screening by Means of Multiple Regression Techniques," *Journal of Geophysical Research*, vol. 67, No. 4, Apr., 1962, pp. 1413–1420.
4. H. C. Fritts, "Computer Programs for Tree-Ring Research," *Tree-Ring Bulletin*, vol. 25, Nos. 3–4, 1963, pp. 2–7.
5. H. C. Fritts, "The Continuation of 'A Study of the Physiological Relationships Underlying Correlations of Tree-Ring Width and Climate,'" Report and Proposal to the National Science Foundation, GB–1025, Jan. 1965, 22 pp.
6. H. C. Fritts, D. G. Smith, and M. A. Stokes, "The Biological Model for Paleoclimatic Interpretation of Mesa Verde Tree-Ring Series," in "Contributions of the Wetherill Mesa Archaeological Project," Assembled by Douglas Osborne, *Memoir of the Society for American Archaeology*, vol. 2, Part 2, Oct. 1965 (in press).
7. H. C. Fritts, D. G. Smith, J. W. Cardis, and C. A. Budelsky, "Tree-Ring Characteristics Along a Vegetational Gradient in Northern Arizona," *Ecology*, vol. 46, 1965 (in press).
8. H. C. Fritts, D. G. Smith, C. A. Budelsky, and J. W. Cardis, "The Variability of Ring Characteristics Within Trees as Shown by a Reanalysis of Four Ponderosa Pine," *Tree-Ring Bulletin*, vol. 27, 1965, (in press).
9. E. Schulman, "An 800-Year Douglas-Fir at Mesa Verde," *Tree-Ring Bulletin*, vol. 14, No. 1, 1947, pp. 2–8.
10. E. Schulman, "Dendrochronology at Navajo National Monument," *Tree-Ring Bulletin*, vol. 14, No. 3, 1948, pp. 18–24.
11. E. Schulman, "Dendrochronology in Northeastern Utah," *Tree-Ring Bulletin*, vol. 15, Nos. 1–2, 1948, pp. 2–14.
12. E. Schulman, *Dendroclimatic Changes in Semiarid America*, University of Arizona Press, Tucson, 1956, 142 pp.
13. S. D. Scott, *Tree-Ring Dating in Mexico*, Ph. D. dissertation, University of Arizona, Tucson, 1963, (pp. 137–138).
14. T. L. Smiley, S. A. Stubbs, and B. Bannister, "A Foundation for the Dating of Some Late Archaeological Sites in the Rio Grande Area, New Mexico," *University of Arizona Bulletin*, vol. 24, No. 3, 1953, pp. 54–55.
15. M. A. Stokes, "Dendroclimatology of the Sacramento Mountains, New Mexico," U.S. Air Force Report, Contract AF19(604)–7474, 1961, 7 pp.

[Received February 5, 1965; revised May 17, 1765]

New Weather Bureau Publication

Research Progress and Plans of the U.S. Weather Bureau, Fiscal Year 1964, Washington, D.C., Jan. 1965, 150 pp. For Sale by Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. Price $1.00.

Annual report of progress made on the research program of the Weather Bureau in the fiscal year ending July 1964, and plans for continued research in fiscal year 1965.